Gamma-rays and neutrinos from the interaction of cosmic rays in the Galaxy

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with
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What Next: sezione d'urto di neutrini,
Bologna 2015

IceCube measured ν events

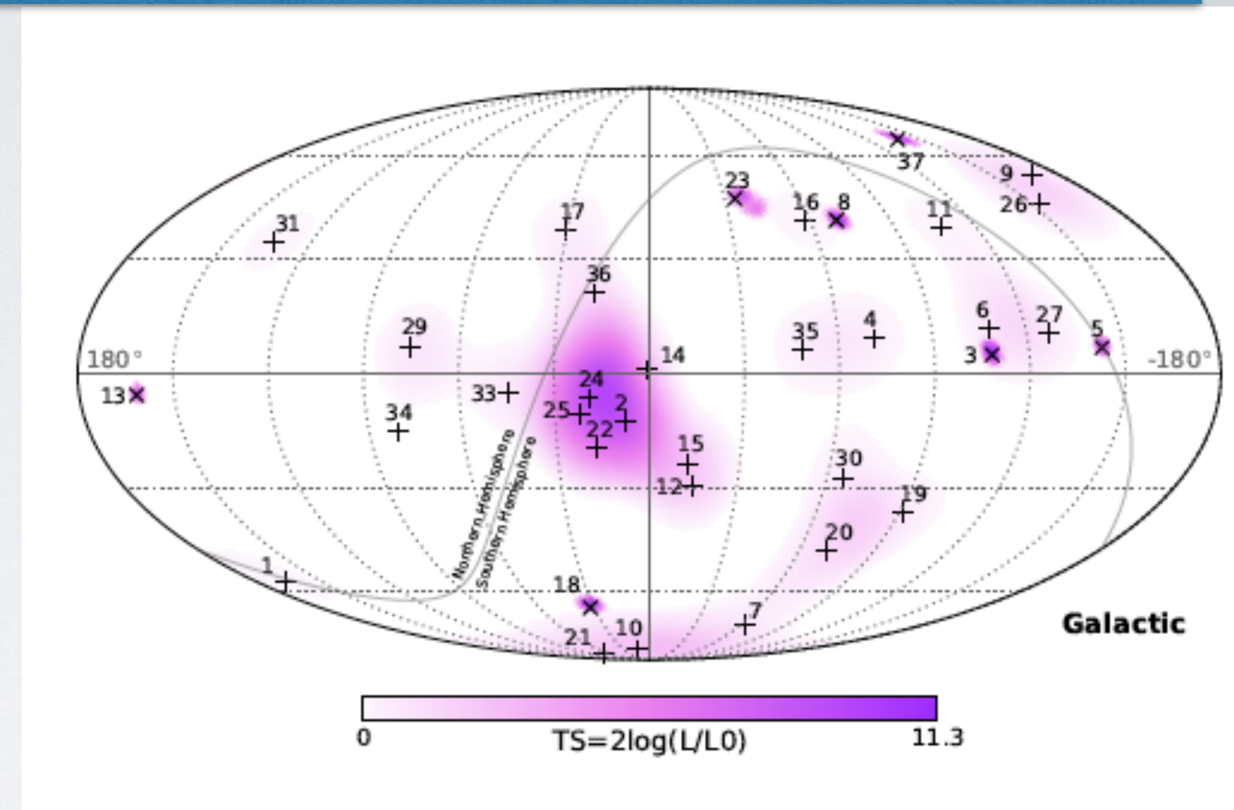
IceCube found evidence for 28 (2 years, PRL 2013) then 37 events (3 yrs PRL 2014) with reconstructed direction above 30 TeV corresponding to a
5.7σ excess respect to the atm. bkg.

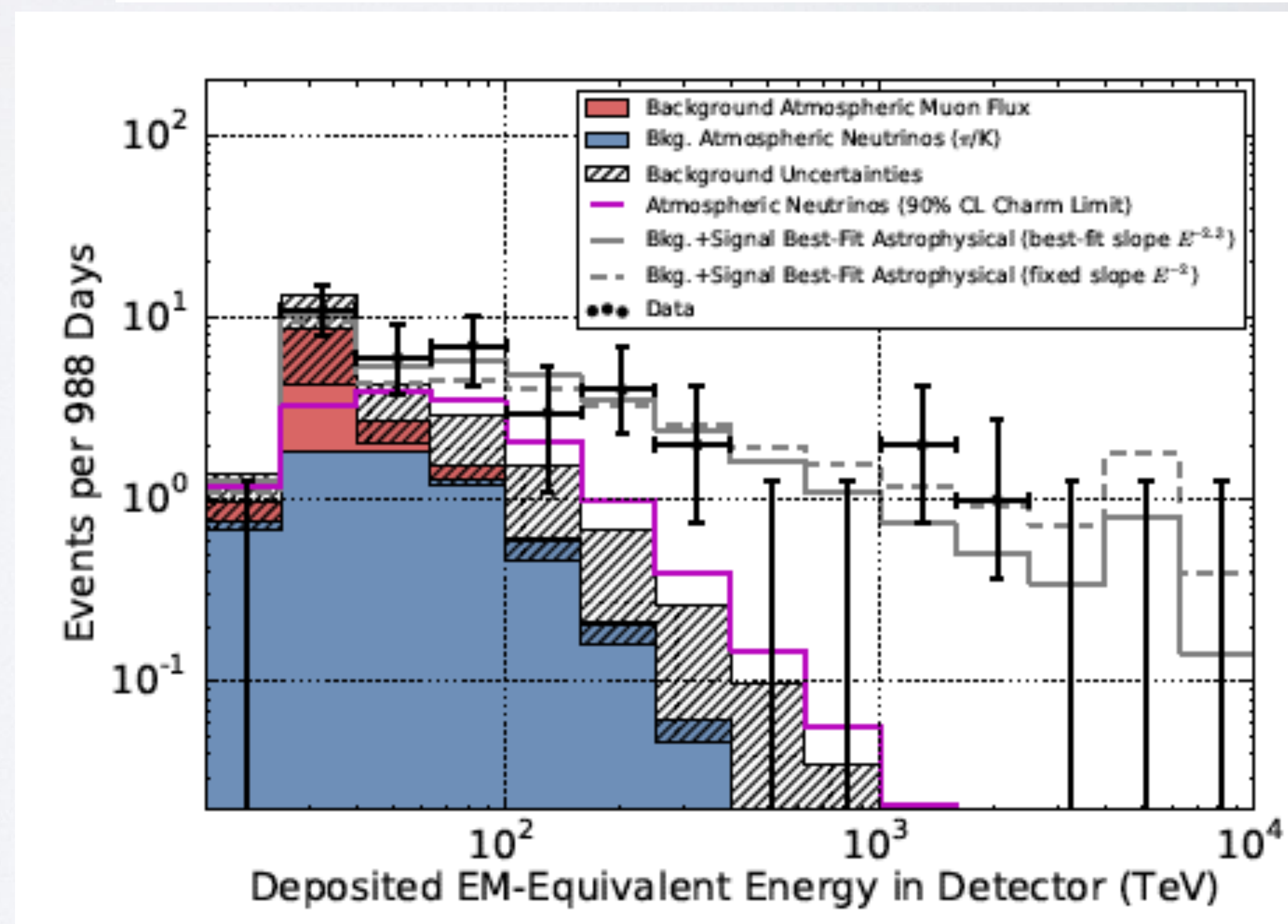
angular distribution compatible with isotropy (see however below)

composition compatible with a equal mixture of e, μ, τ as expected for astrophysical generated neutrino

Best fit spectral index - 2.3 ± 0.3

Slightly softer than expected for extragalactic astrophysical source





IceCube measured ν events (4-years)

IceCube found evidence for 54 events (4 yrs preliminary) with reconstructed direction above 30 TeV corresponding to

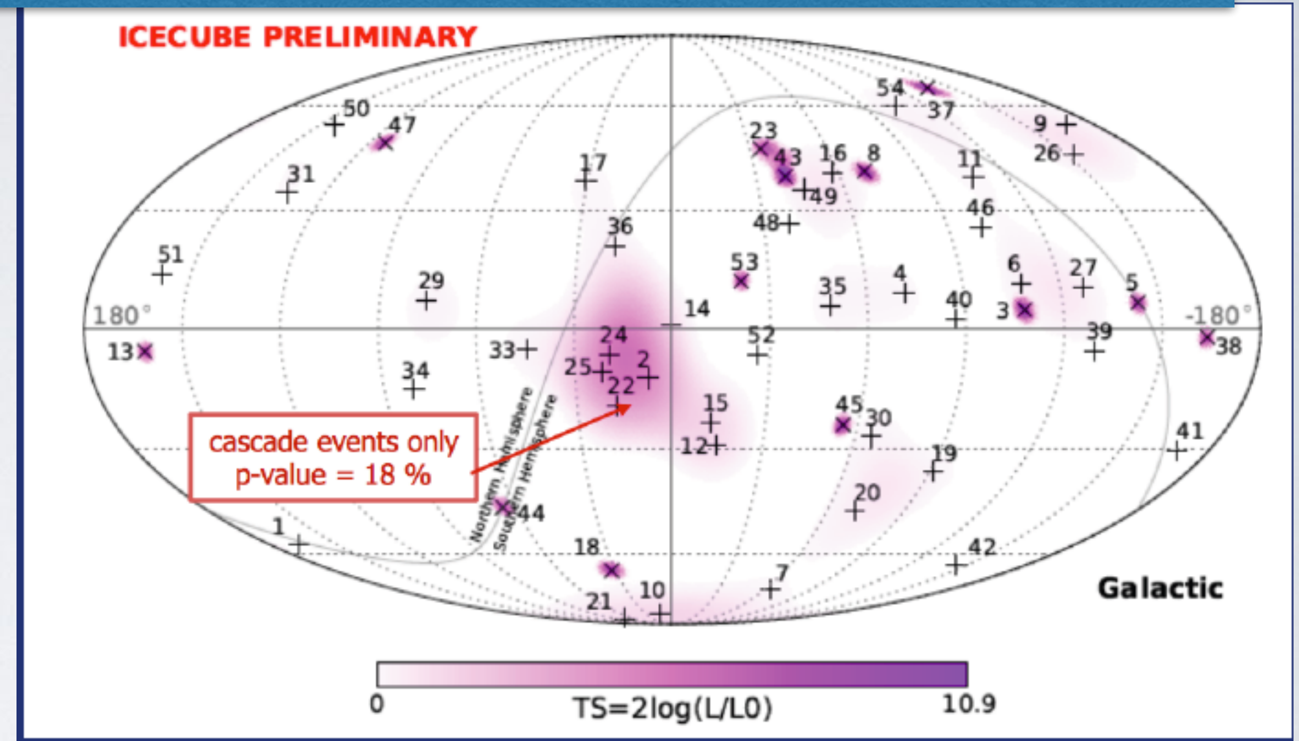
7σ excess respect to the atm. bkg. $(9^{+8}_{-2.2})$

angular distribution compatible with isotropy (see however below)

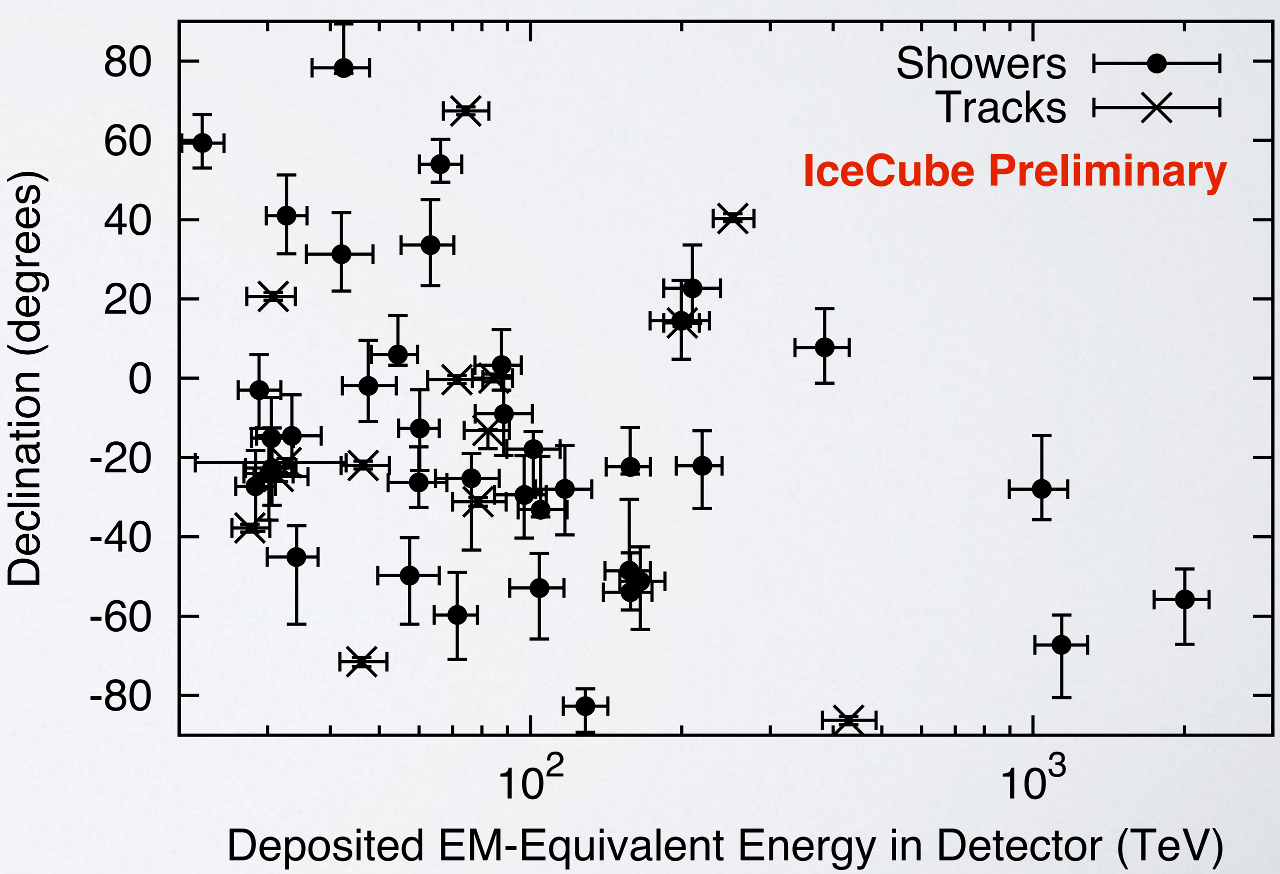
composition compatible with a equal mixture of e, μ, τ as expected for astrophysical generated neutrino

Best fit spectral index $\Gamma \sim -2.58 \pm 0.25$

Significantly softer than expected for extragalactic astrophysical source



O. Botner (IPA2015)



IceCube measured ν events (4-years)

Kopper et al., ICRC (2015)

IceCube found evidence for 54 events (4 yrs preliminary) with reconstructed direction above 30 TeV corresponding to

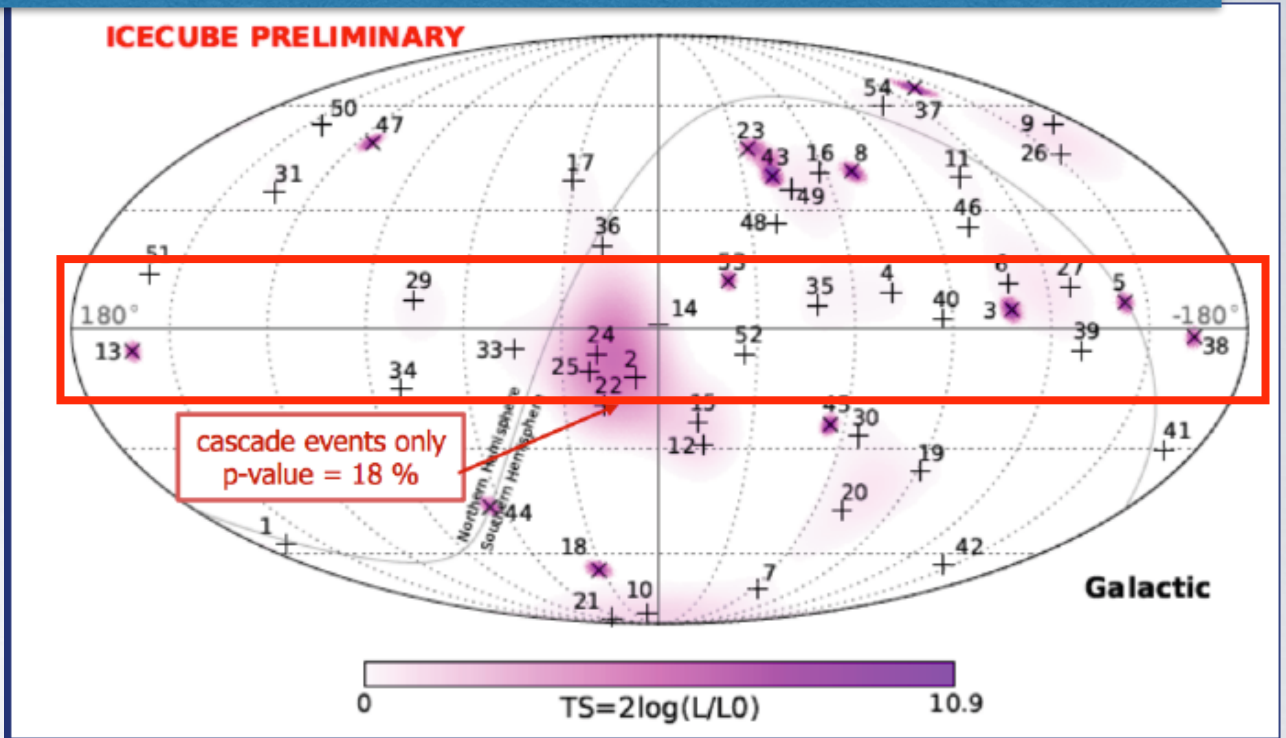
7σ excess respect to the atm. bkg. ($9^{+8}{}_{-2.2}$)

angular distribution compatible with isotropy (see however below)

composition compatible with a equal mixture of e, μ, τ as expected for astrophysical generated neutrino

Best fit spectral index Γ ~ - 2.58 ± 0.25

Significantly softer than expected for extragalactic astrophysical source



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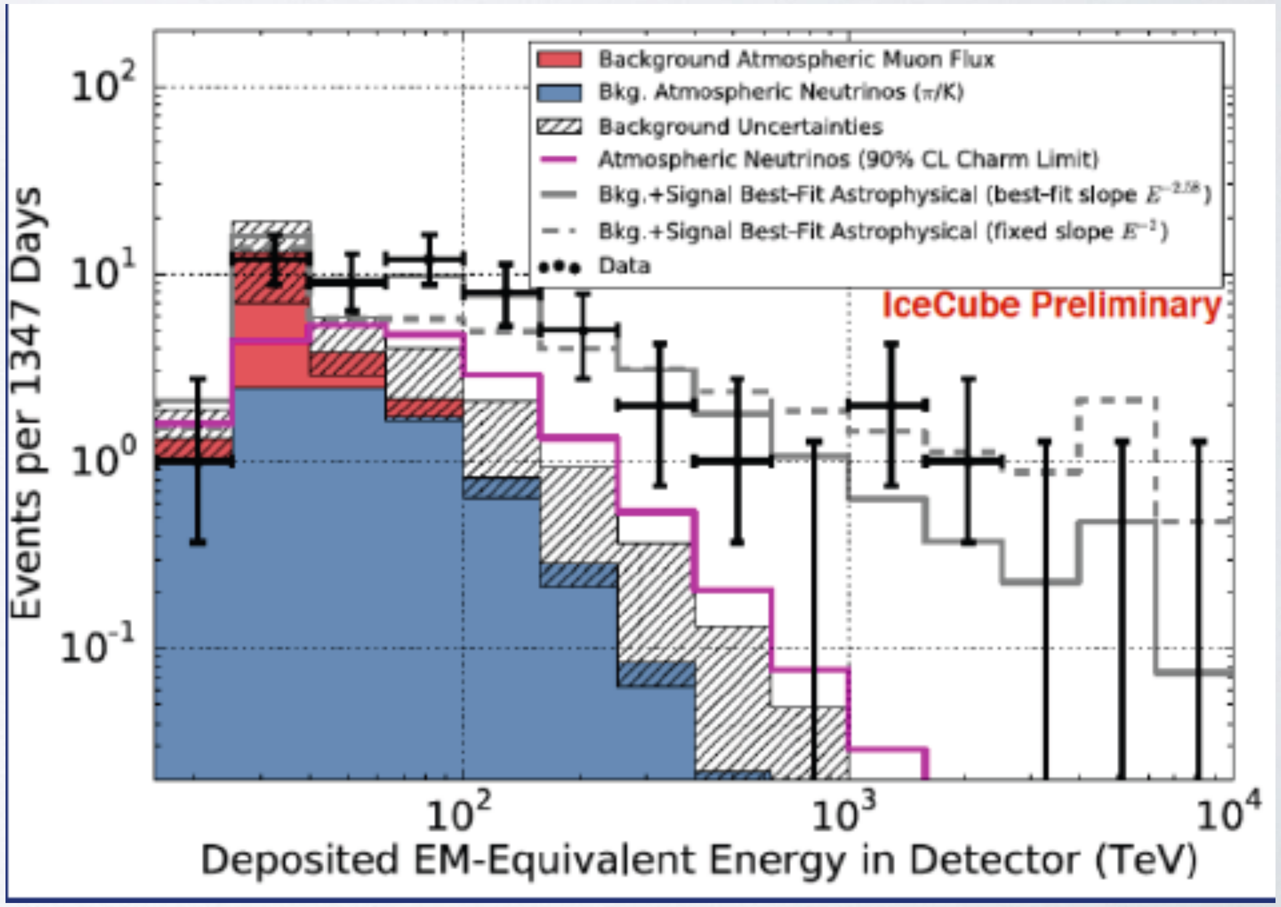
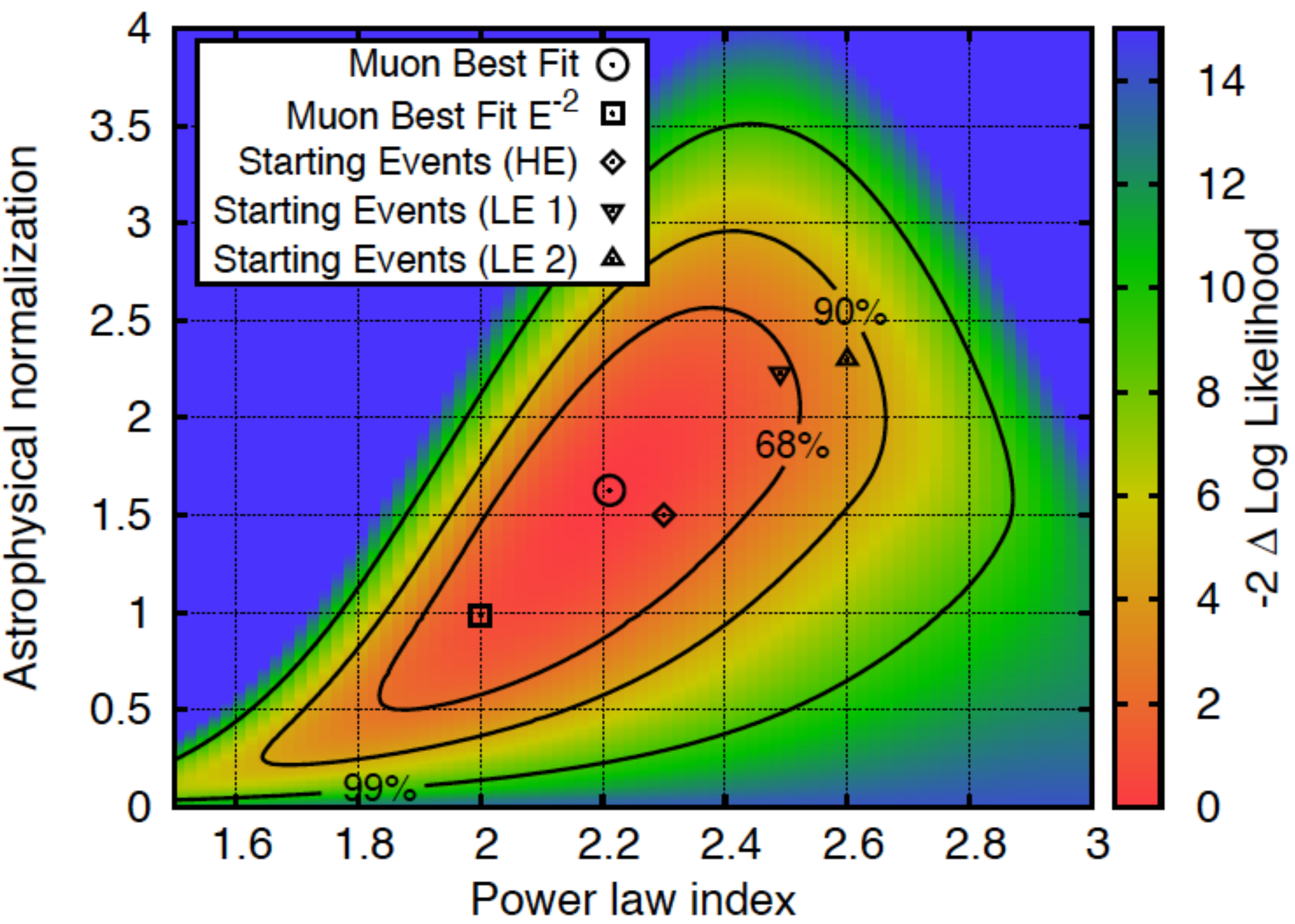
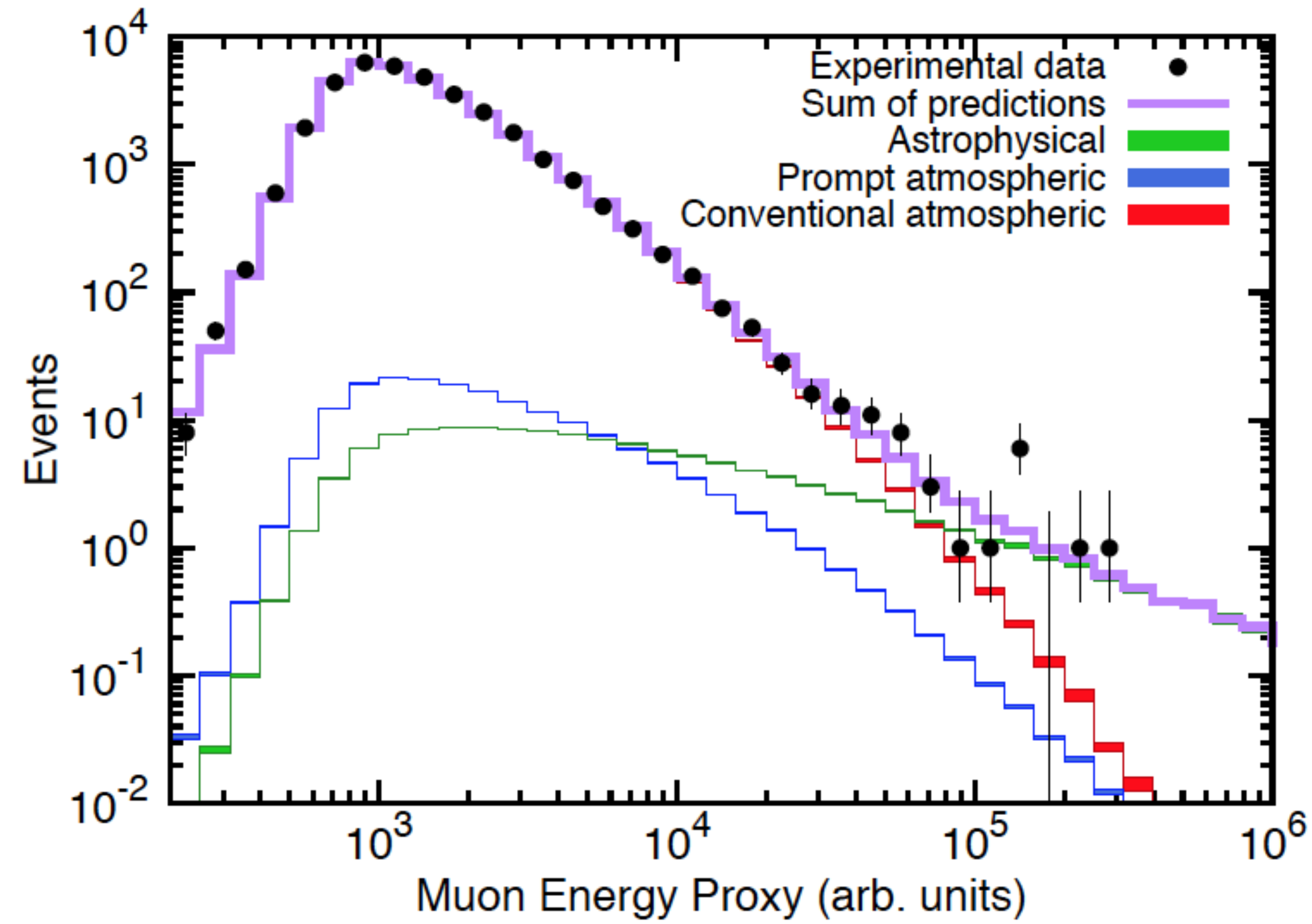


Estimating the extragalactic contribution from the North hemisphere

IceCube coll., PRL, vol.115, 2015





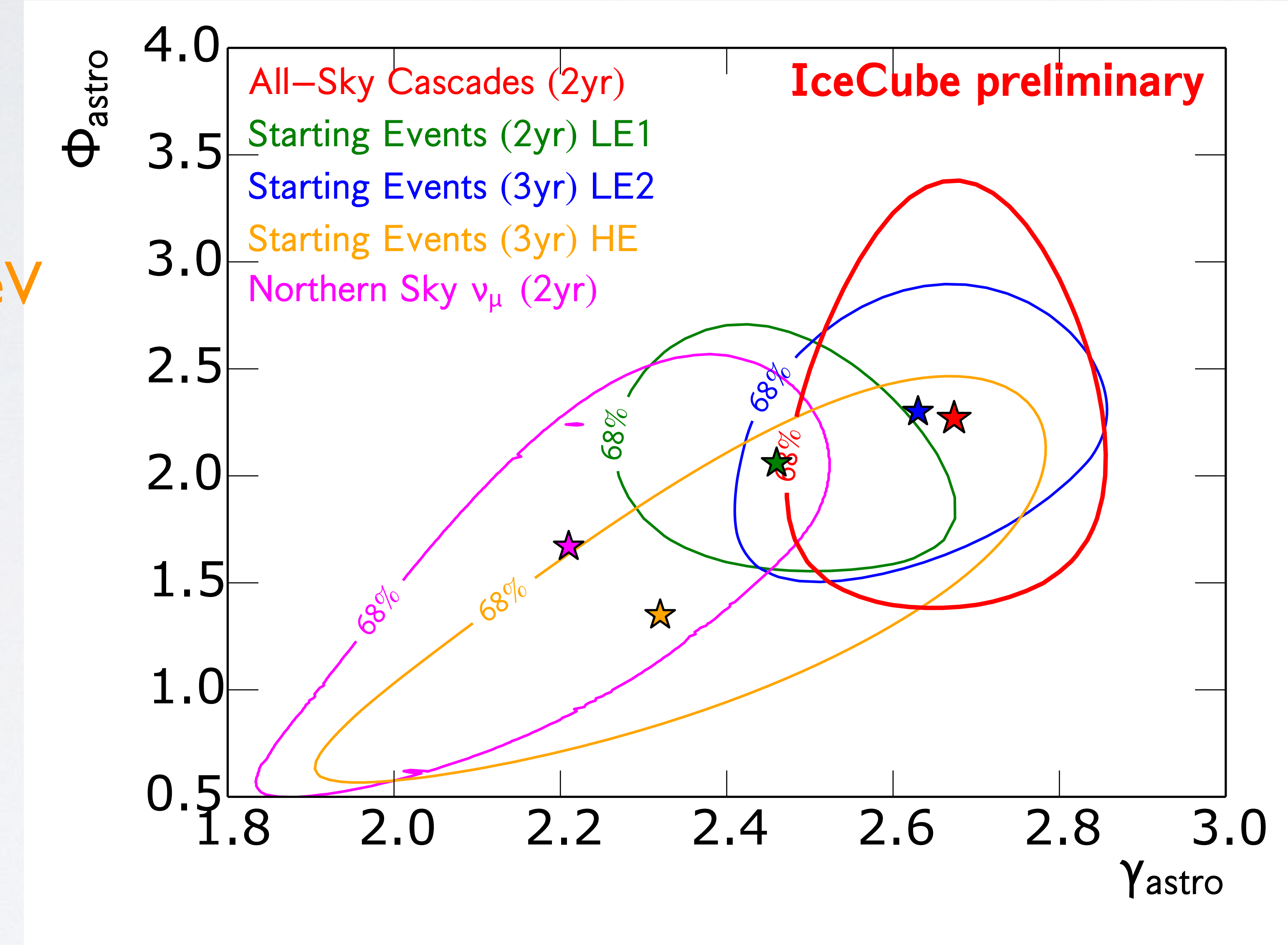
- astrophysical muon neutrinos from the Northern hemisphere with E > 100 TeV.
The neutrinos collected during 659.5 days of live time between May 2010 and May 2012 are inconsistent with the background at the level of **3.7 σ**.

- Assuming a single power-law the best-fit spectral index is $\Gamma = 2.2 \pm 0.2$.

Hints of an anisotropic flux ?

IceCube coll., Niederhausen, ICRC 2015 arXiv:1510.05223

ICRC (2015), E > 10 TeV
PRD 91, (2015) all event E > 1 TeV
PRL 114 (2015), HESE E > 35 TeV
PRL 101101 (2014), HESE E > 60 TeV
PRL 115 (2015) ν_μ, E > 100 TeV



$\phi_{north} = 1.7^{+1.3}_{-1.2}\,\mathrm{GeV}^{-1}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{cm}^{-2}$, $\phi_{south} = 1.9^{+0.8}_{-0.6}\,\mathrm{GeV}^{-1}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{cm}^{-2}$ $\times\ 10^{-18}$ per flavor

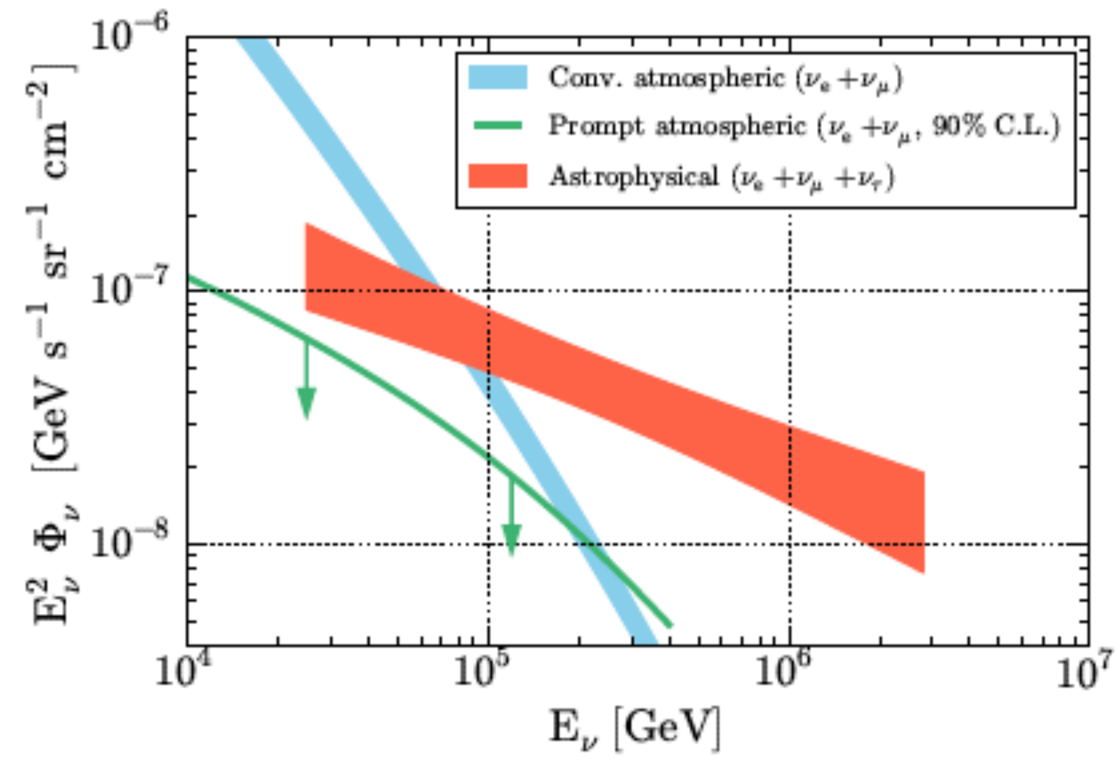
$\gamma_{north} = 2.69^{+0.34}_{-0.34}$, $\gamma_{south} = 2.68^{+0.20}_{-0.22}$ ICRC (2015), E > 10 TeV

Hints of an anisotropic flux ?

ApJ 2015

A recent template fitting analysis of a larger number of events, including those with unreconstructed direction and with E > 25 TeV found a steeper spectrum for the astrophysical neutrino component.
Best fit single power-law spectral index

- 2.50 ± 0.09 !



Parameter	Best fit	68% C.L.	90% C.L.
ϕ_N	2.1	0.5 – 5.0	0.1 – 7.3
γ_N	2.0	1.6 – 2.3	1.2 – 2.5
ϕ_S	6.8	5.3 – 8.4	4.4 – 9.5
γ_S	2.56	2.44 – 2.67	2.36 – 2.75

Note. — ϕ_N and ϕ_S are the all-flavor neutrino fluxes at 100 TeV in the northern and southern sky, respectively; γ_N and γ_S are the corresponding spectral indices. The fluxes are given in units of $10^{-18}\,\mathrm{GeV^{-1} s^{-1} sr^{-1} cm^{-2}}$.

a North-South analysis favors (low significance take with caution !) a larger and flatter spectrum from the South hemisphere

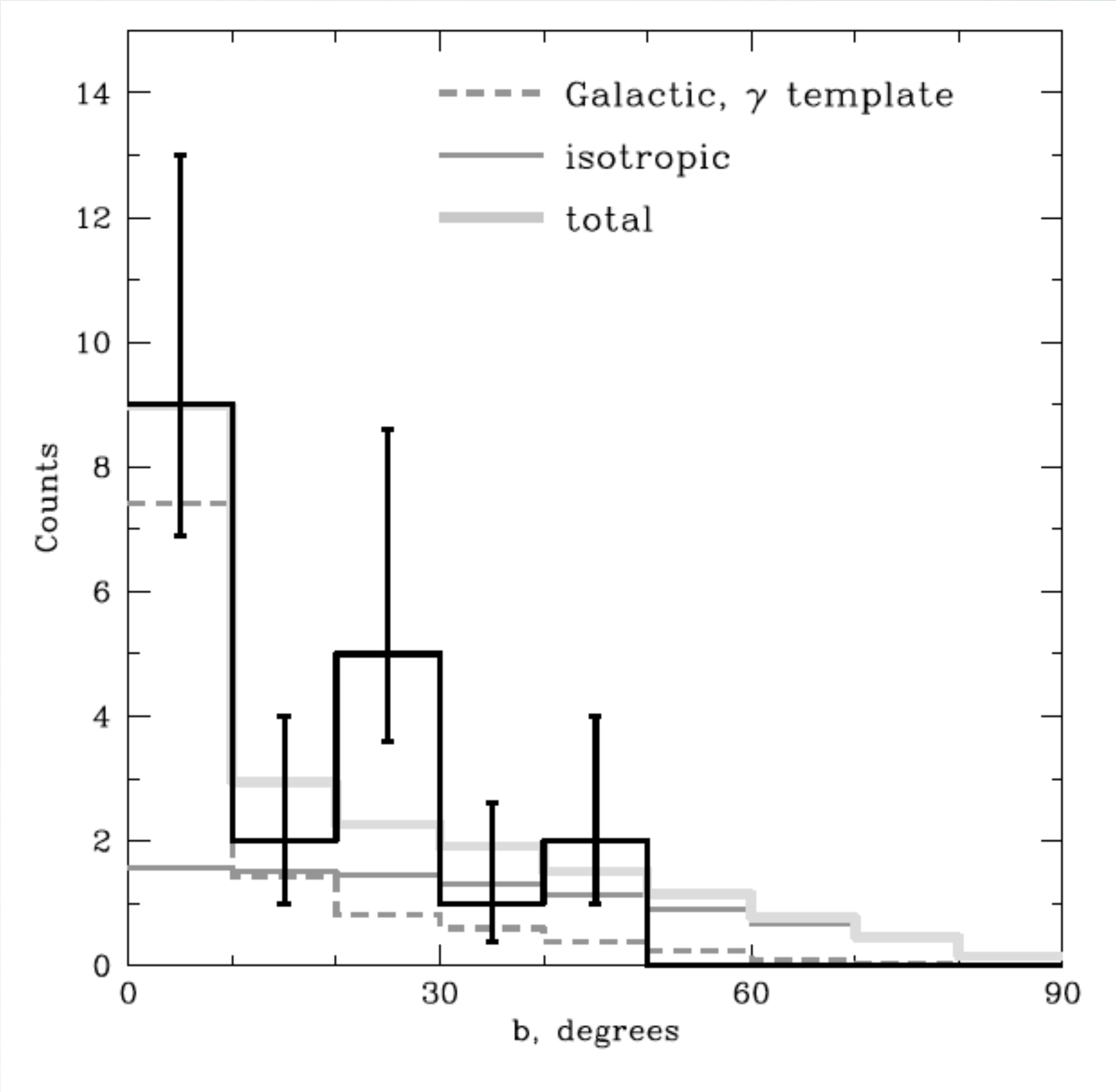
all this might be indicating the presence of a significant Galactic component !

Hints of an anisotropic flux ?

To reduce contamination from atm. ν they use only events above 100 TeV in the IC 4-year sample (19 events, 1 bkg)

Neronov & Semikoz *arXiv:1509.03522*

9 events are found for | b | < 10°   0 events are found for | b | > 50°



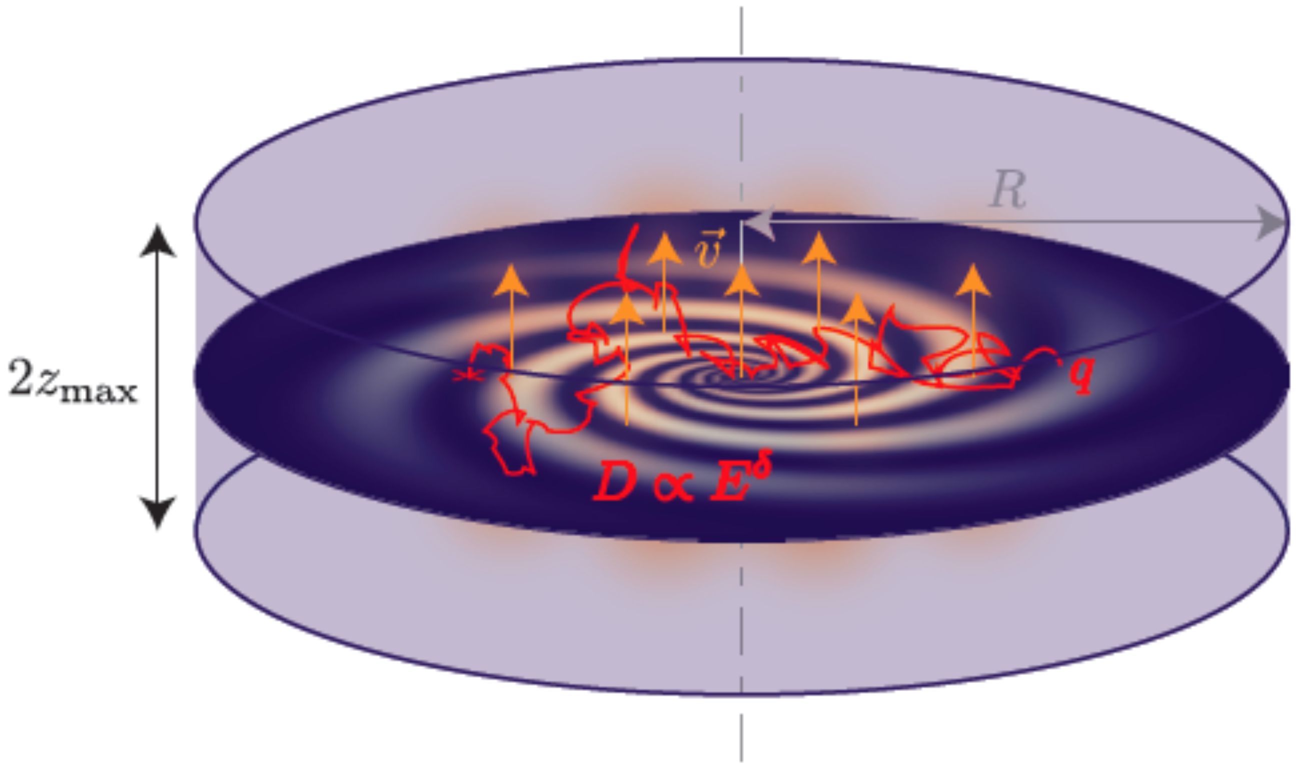
A MC with an isotropic flux gives the same results with $p = 7 \times 10^{-5}$
(~ 4 σ inconsistency)

It is claimed that "*a model which contains 50% contributions from the Galactic and extragalactic components provides a satisfactory fit to the data*"

this is the maximum contribution form the Galactic plane allowed by IC according to

Ahlers et al. 2015

The conventional propagation scenario for cosmic rays



ρ : particle rigidity

D : diffusion coefficient

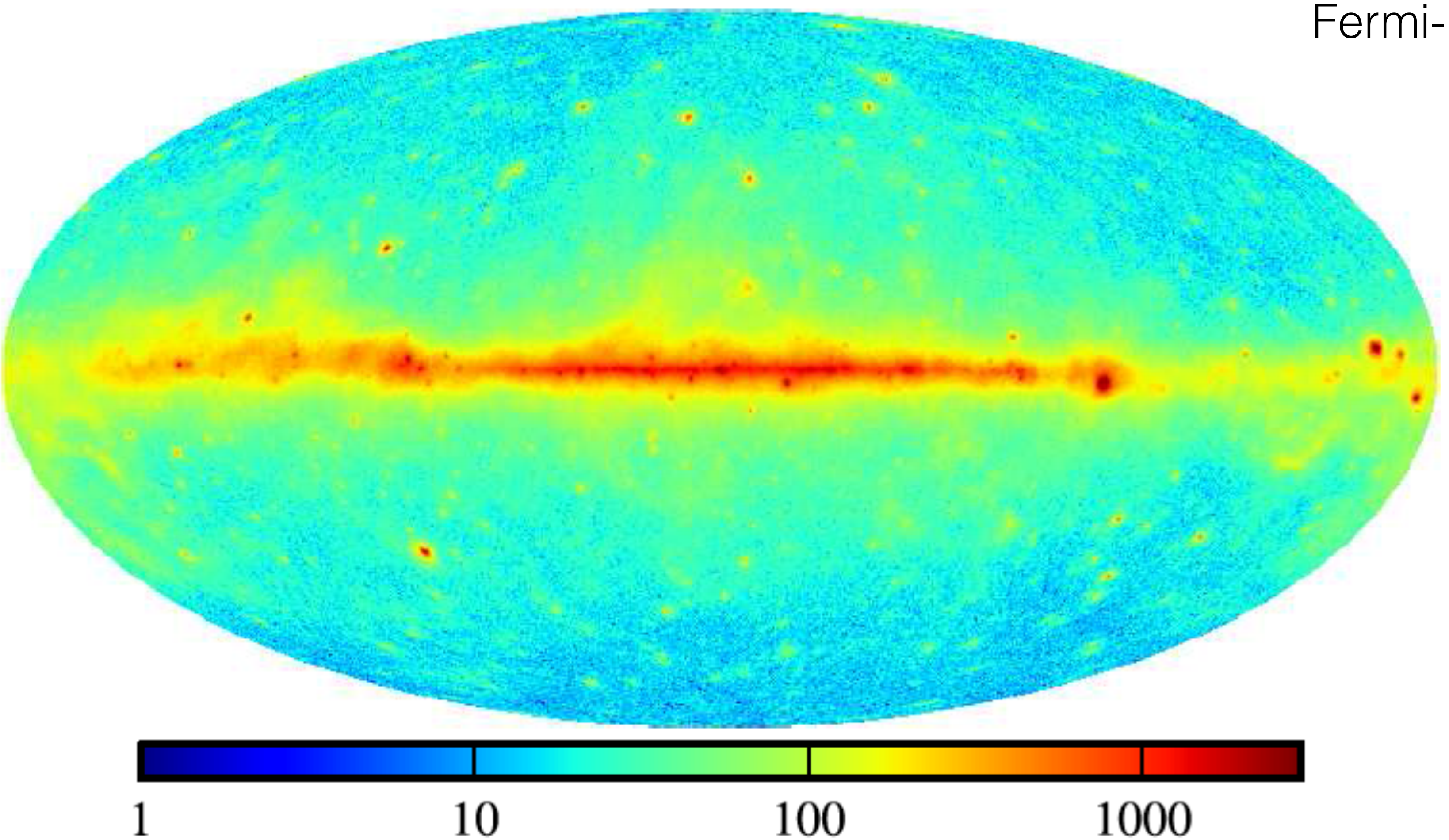
R : distance from galaxy center

- The diffusion coefficient $D \propto \rho^{\delta}$, in a conventional scenario δ is uniform and
- parameters are tuned against local CR spectra and the secondary/primary ratios.

These quantities however probe only few kpc's about our position.
Propagation may behave quite differently in the inner few kpc of the Galaxy !

Diffuse Galactic Plane gamma-ray emission

Fermi-LAT coll. APJ 2012



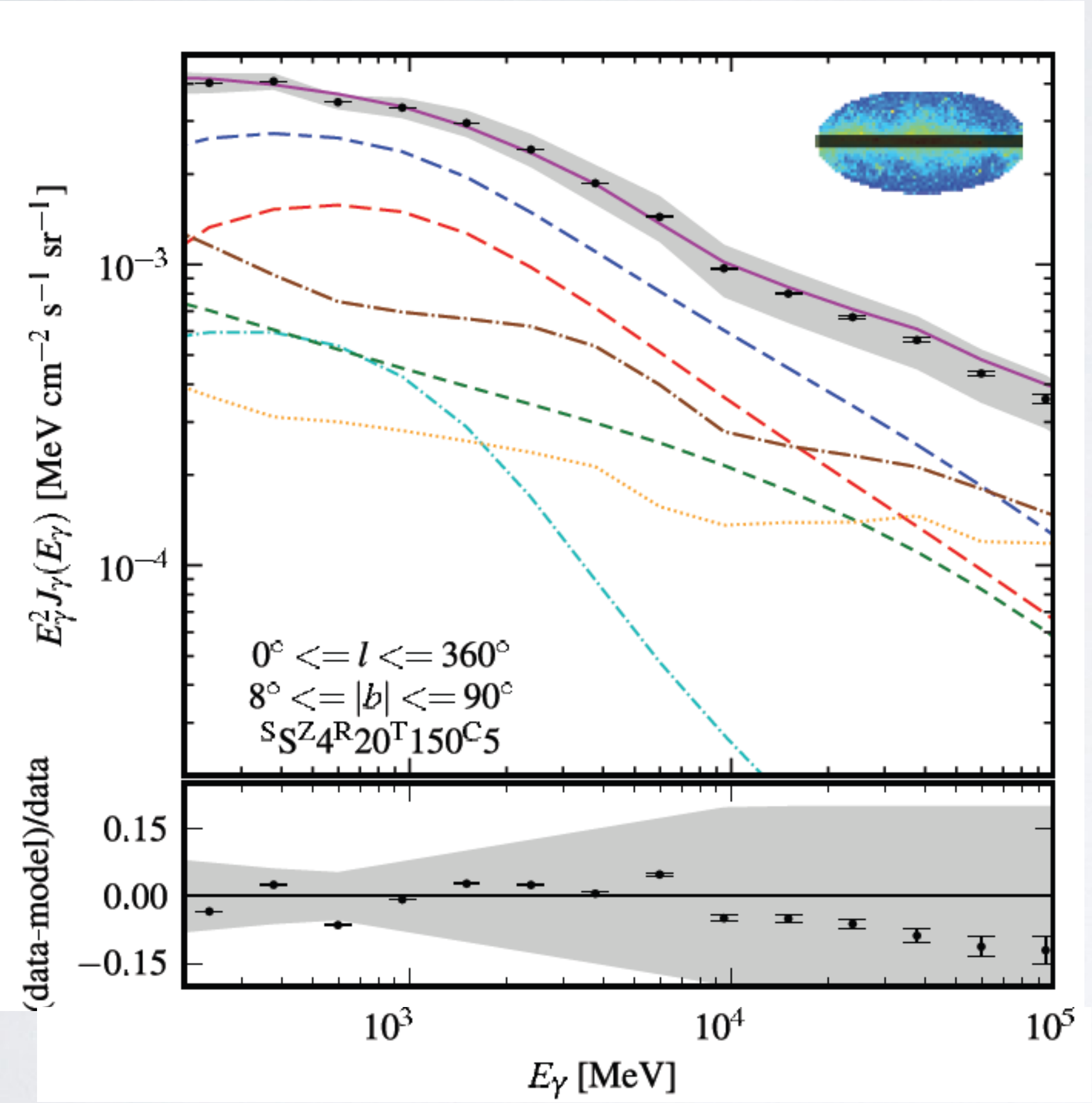
Observed Fermi-LAT counts in the energy range 200 MeV to 100 GeV after point-sources subtraction (log scale = counts/pixel)

The gamma-ray diffuse emission is mainly related:

- Photopion production due to the CR/gas collision - Dominant for the inner GP, produce also ν
- Bremsstrahlung of relativistic electrons in gas
- Inverse-Compton of relativistic electrons with ISRF

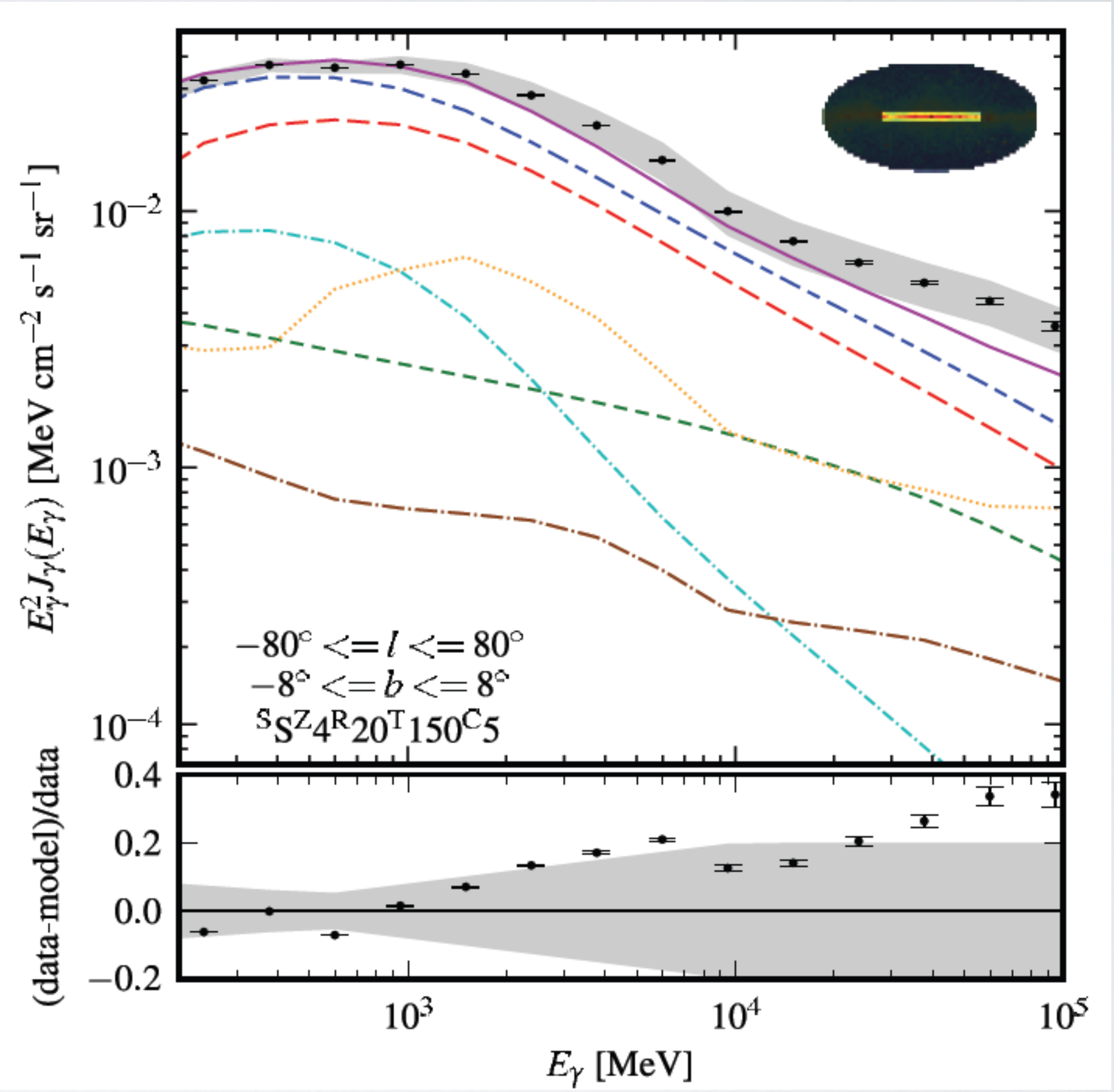
Conventional models against Fermi data

full-sky but the GP



inner GP

Fermi coll. ApJ 2012



Fermi Benchmark (FB) conventional model:

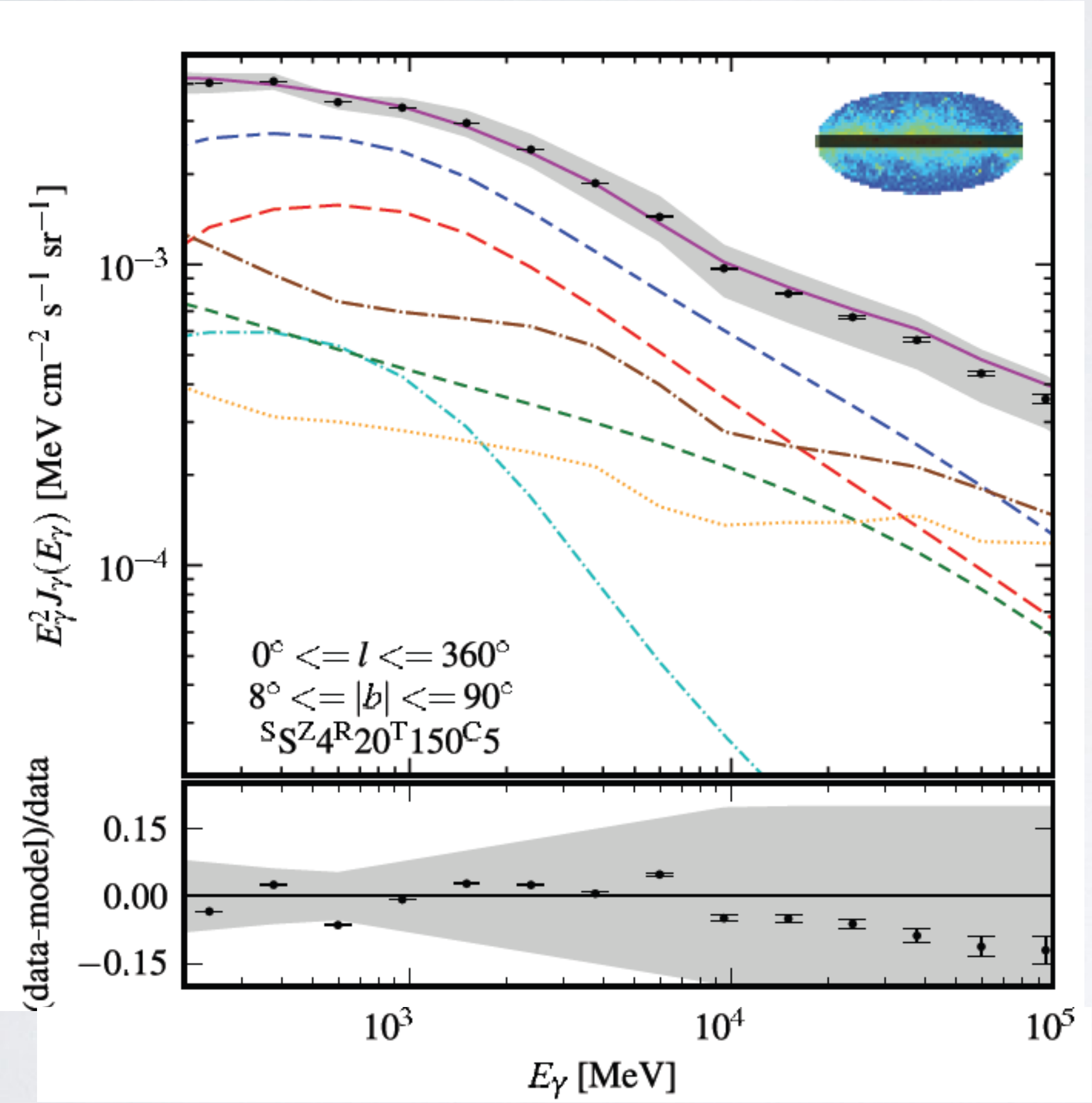
δ = 0.3 , γ_P = 2.72 (in the whole Galaxy), z_h = 4 kpc

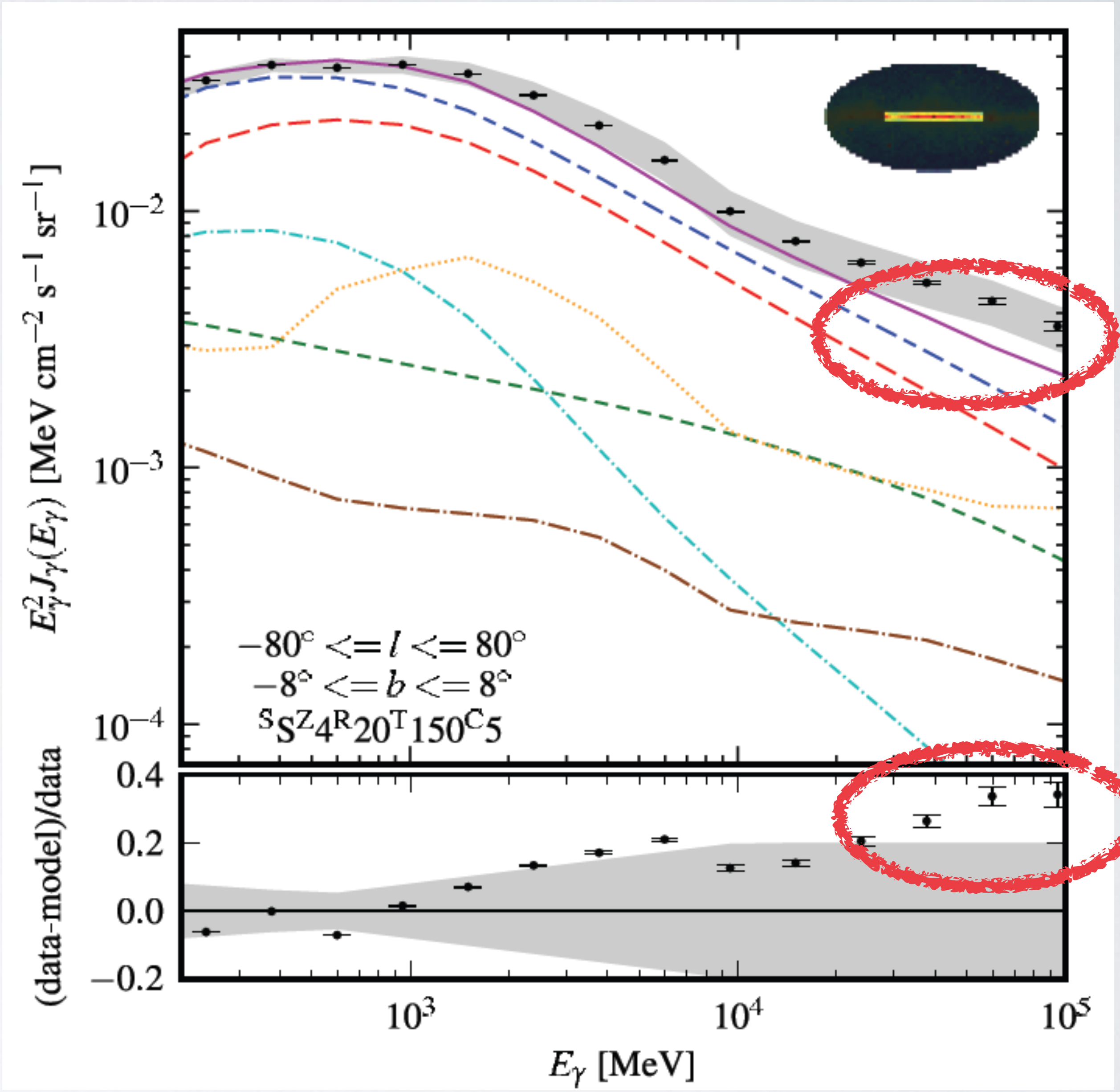
Conventional models against Fermi data

full-sky but the GP

inner GP

Fermi coll. ApJ 2012





Fermi Benchmark (FB) conventional model:

$\delta = 0.3$, $\gamma_P = 2.72$ (in the whole Galaxy), $z_h = 4$ kpc

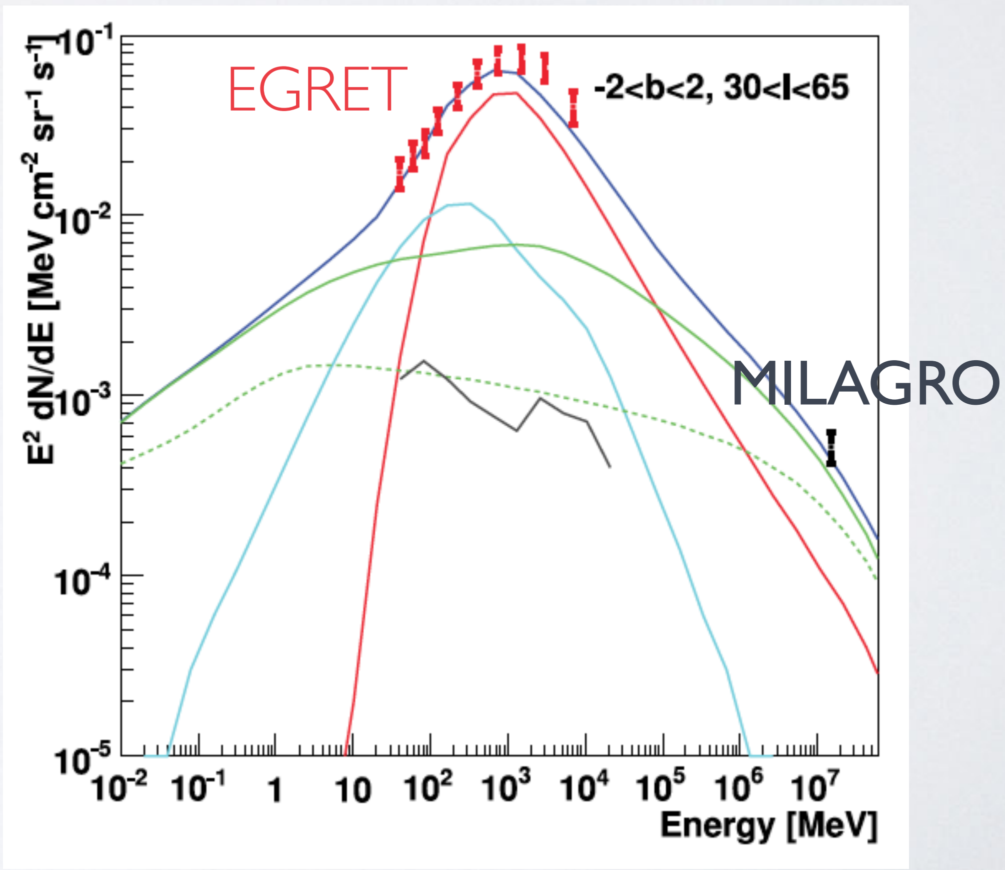
The Milagro anomaly in the inner Galactic Plane

ABDO ET AL. *ApJ 2008*

TABLE 1

Gamma-Ray Emission from the Galactic Plane around 15 TeV

Region for $\|b\| < 2°$ (l, deg)	Statistical Significance σ	Diffuse Flux ($\times 10^{-13}$ TeV^{-1} cm^{-2} s^{-1} sr^{-1})		
			GALPROP	
		Milagro[a]	Optimized	Conventional
30–65	5.1	$23.1 \pm 4.5^{+7.0}_{-8.0}$	20.0	4.9

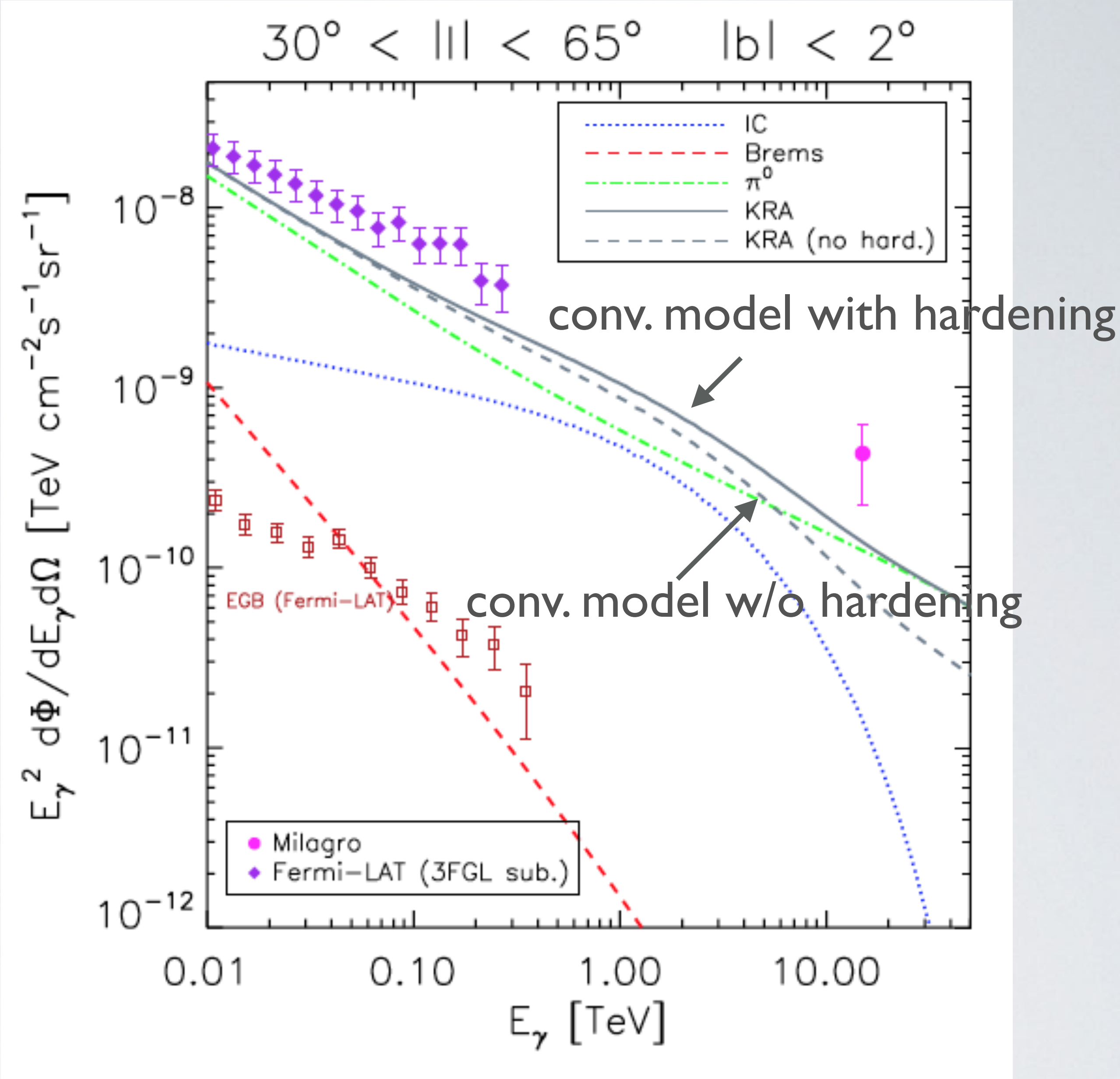


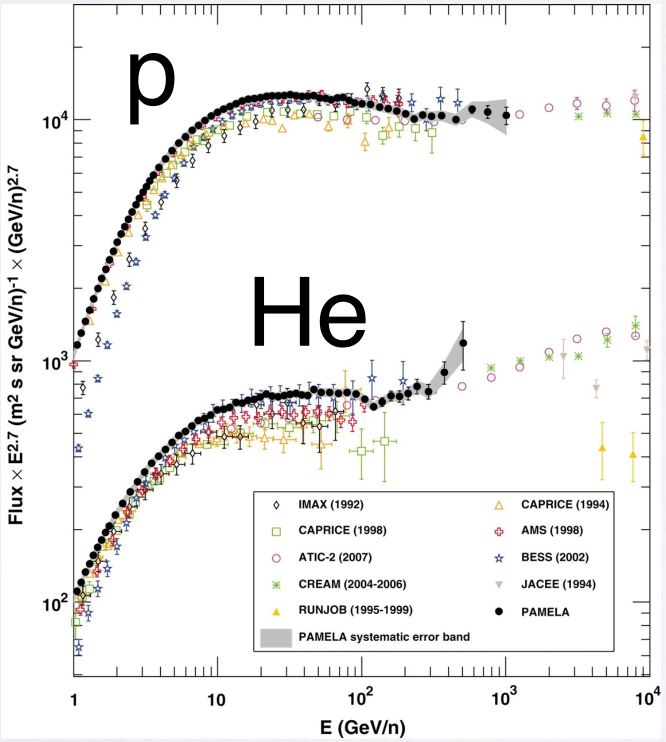
- the measured flux is 5 times (4 σ) larger than computed with the conventional model
- an optimized model (augmented IC contribution) - proposed to account for the EGRET GeV excess - was found to match Milagro

The Milagro anomaly holds on

- Fermi-LAT excluded the GeV excess and the optimized model *Fermi-LAT coll. PRL 2009*
- conventional models tuned against local CR observables and matching the "full-sky" Fermi-LAT diffuse emission do not match Milagro !
- the problem holds even assuming that the p and He spectral harden at ～ 250 GeV

  (required to match PAMELA and AMS-02 and CREAM data)





KRA: representative conv. model tuned against CR spectra (see below). Same result with GALPROP benchmark models (which do not account for hardening)

The KRAγ model: Radial dependency of CR transport

Gaggero, Urbano, Valli & Ullio
arXiV: 1411.7623 PRD 2015

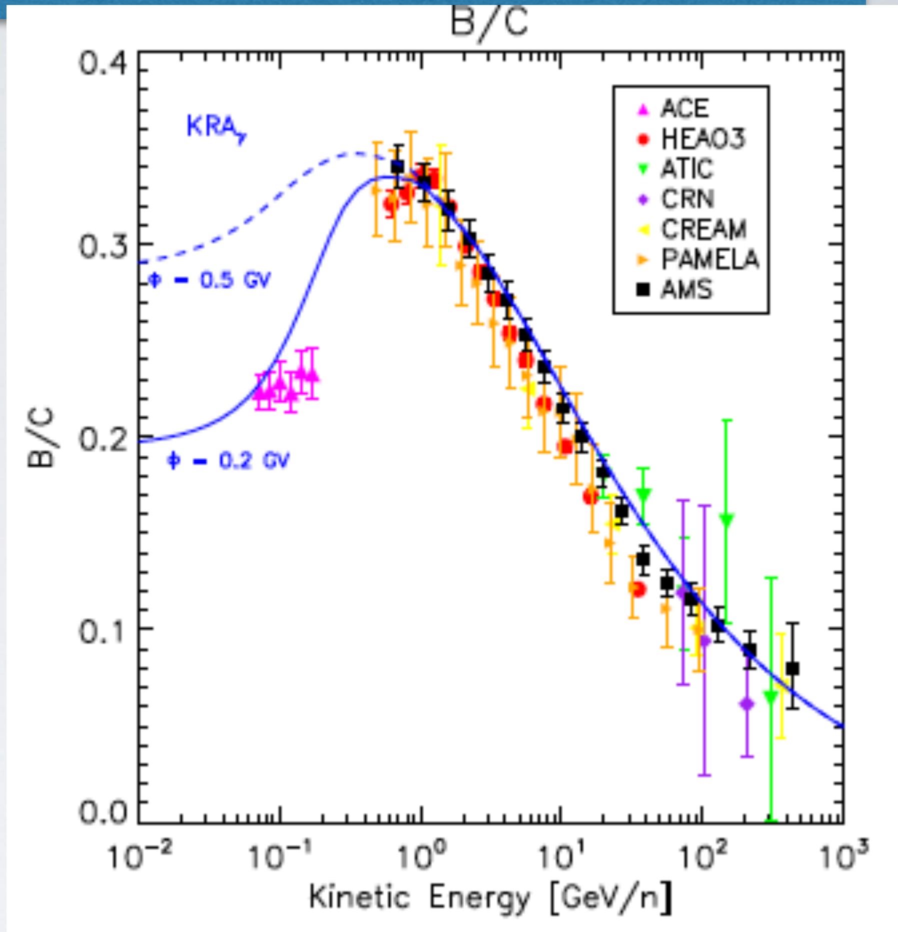
The KRAγ model - implemented with the DRAGON code - adopts a radial dependent diffusion coefficient

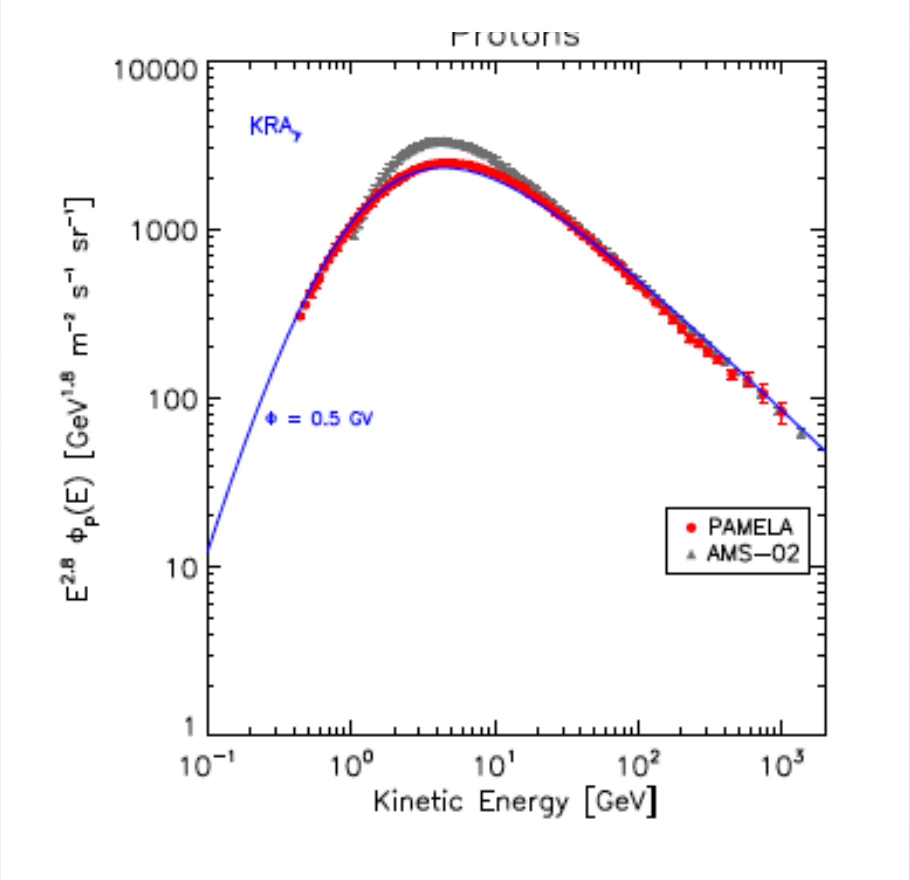
$\delta(R) = A\,R + B$ for R < 11 kpc
such that $\delta(R_{sun}) = 0.5$

and convective velocity

$$\frac{dV_C}{dz} = 100 \text{ km s}^{-1} \text{ kpc}^{-1}$$ for R < 6.5 kpc

The model is tuned to reproduce the proton spectrum measured by PAMELA and B/C (antiprotons also matched by secondary prod.) as well as updated diffuse γ-ray Fermi data

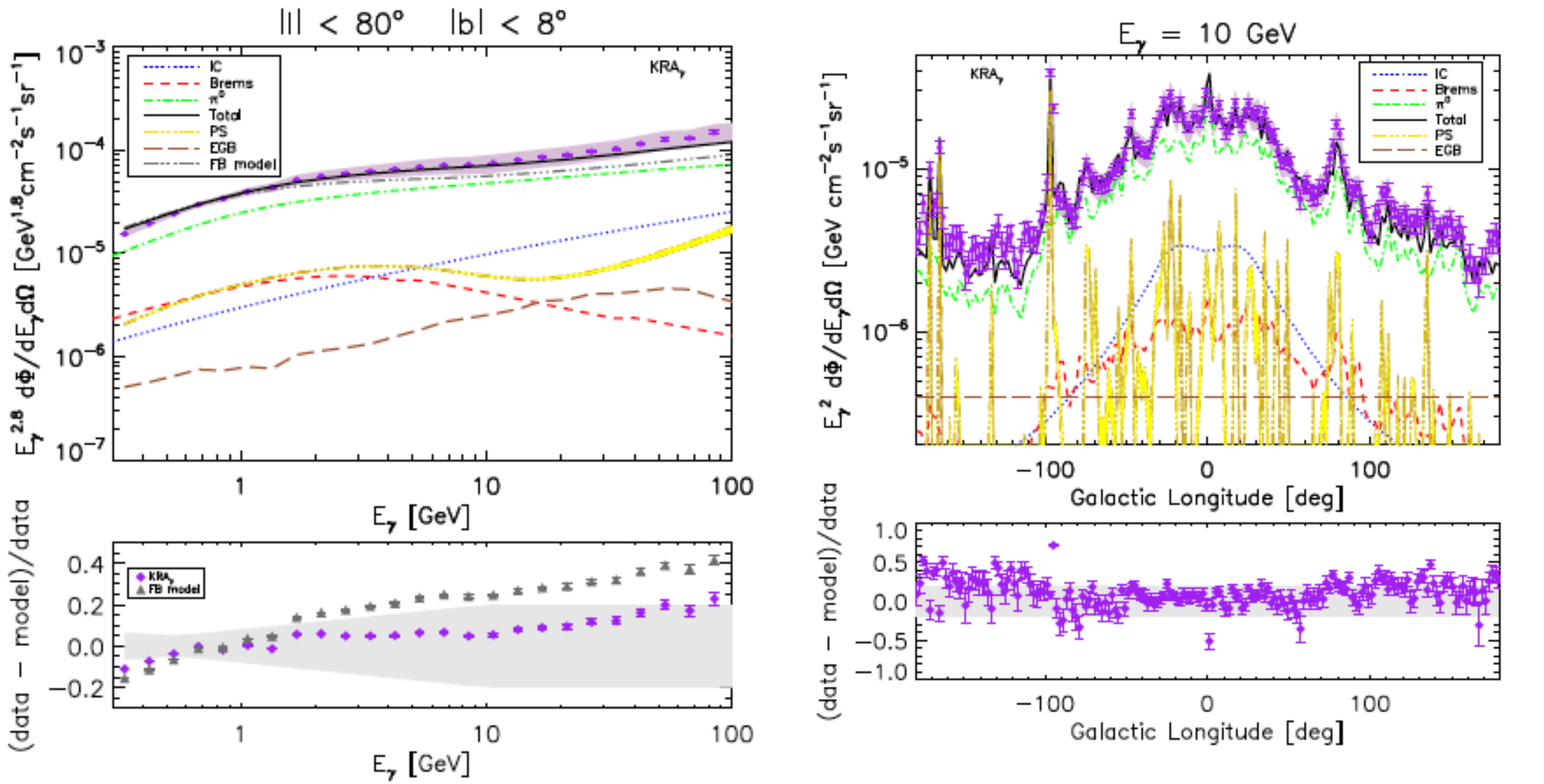




The KRAγ model: Radial dependency of CR transport

The KRAγ model reproduces the full-sky Fermi spectrum and angular distribution. It also provides a better fit in the inner GP region

Gaggero, Urbano, Valli & Ullio
arXiV: 1411.7623 PRD 2015



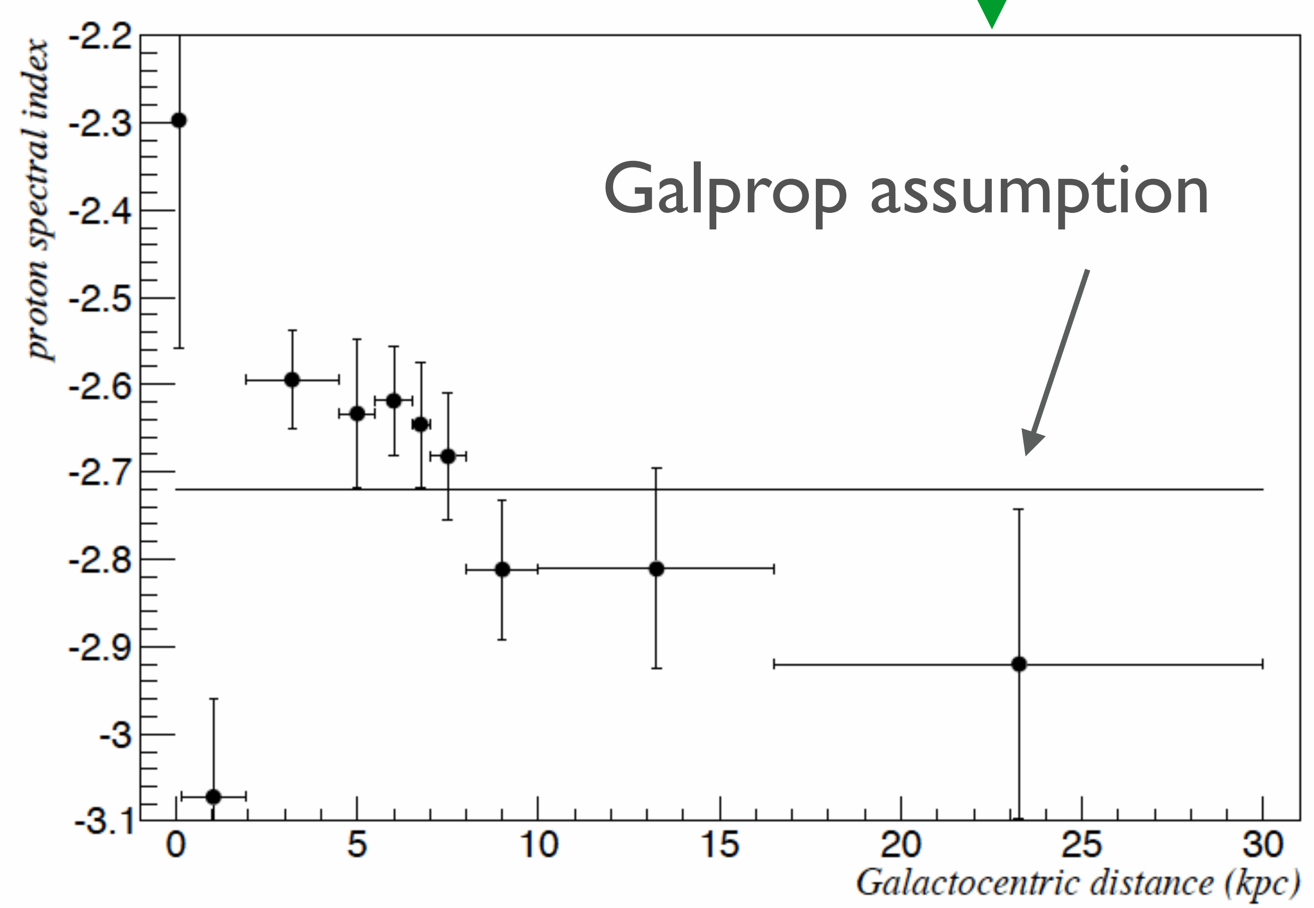
The KRAγ model: Radial dependency of CR transport

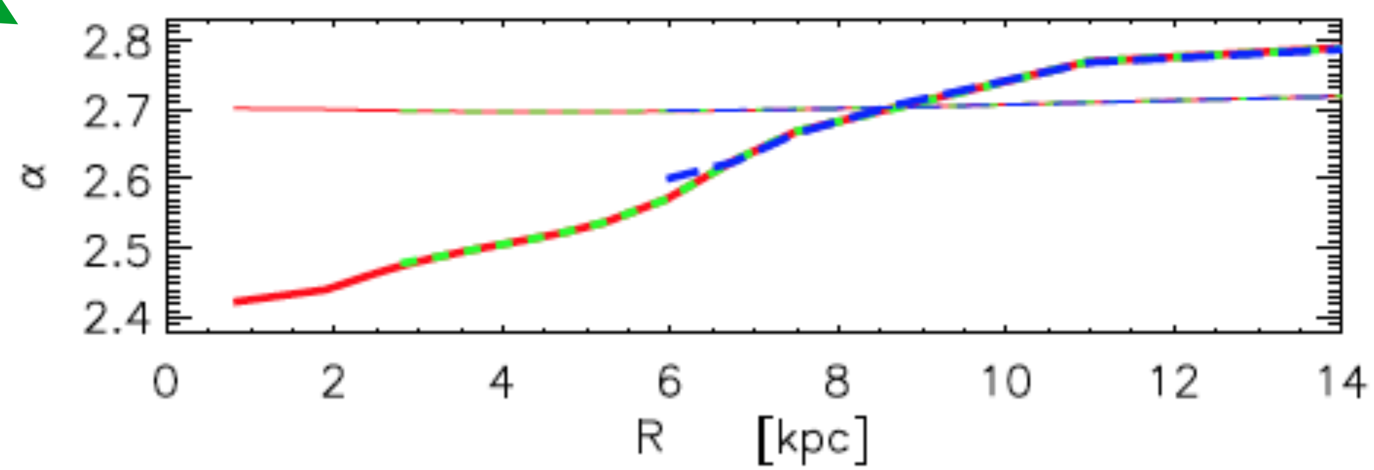
Casandajian [Fermi coll.], 5th Fermi symp. 2014 submitted to ApJ

a template-fitting analysis of the diffuse γ-ray emission measured by Fermi found such evidence

this is incompatible with conventional models implemented with GALPROP

Gaggero et al. 2015 KRAγ model predictions are consistent with such finding !





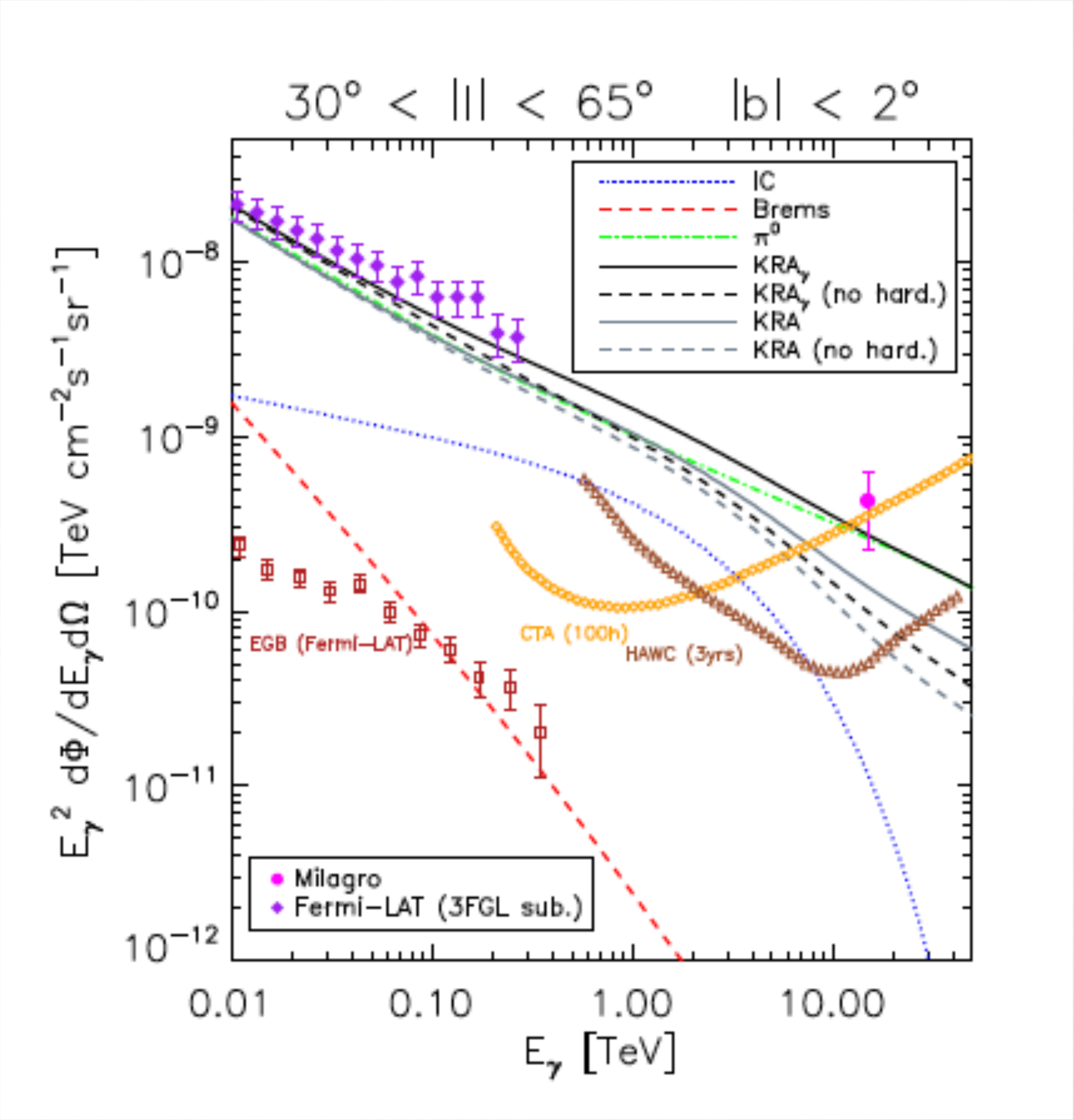
The KRAγ model solves the Milagro anomaly at 15 TeV

Gaggero, D.G., Marinelli Urbano &Valli
arXiV: 1504.00227

The KRAγ model nicely matches MILAGRO consistently with Fermi data (point sources cleaned) without further tuning !

Since the model assumes a CR spectral hardening at 250 GeV/n to match PAMELA and AMS-02
the hardening cannot be a local effect
instead it must be present at least in a large fraction of the inner GP volume !

HAWC may soon test this prediction



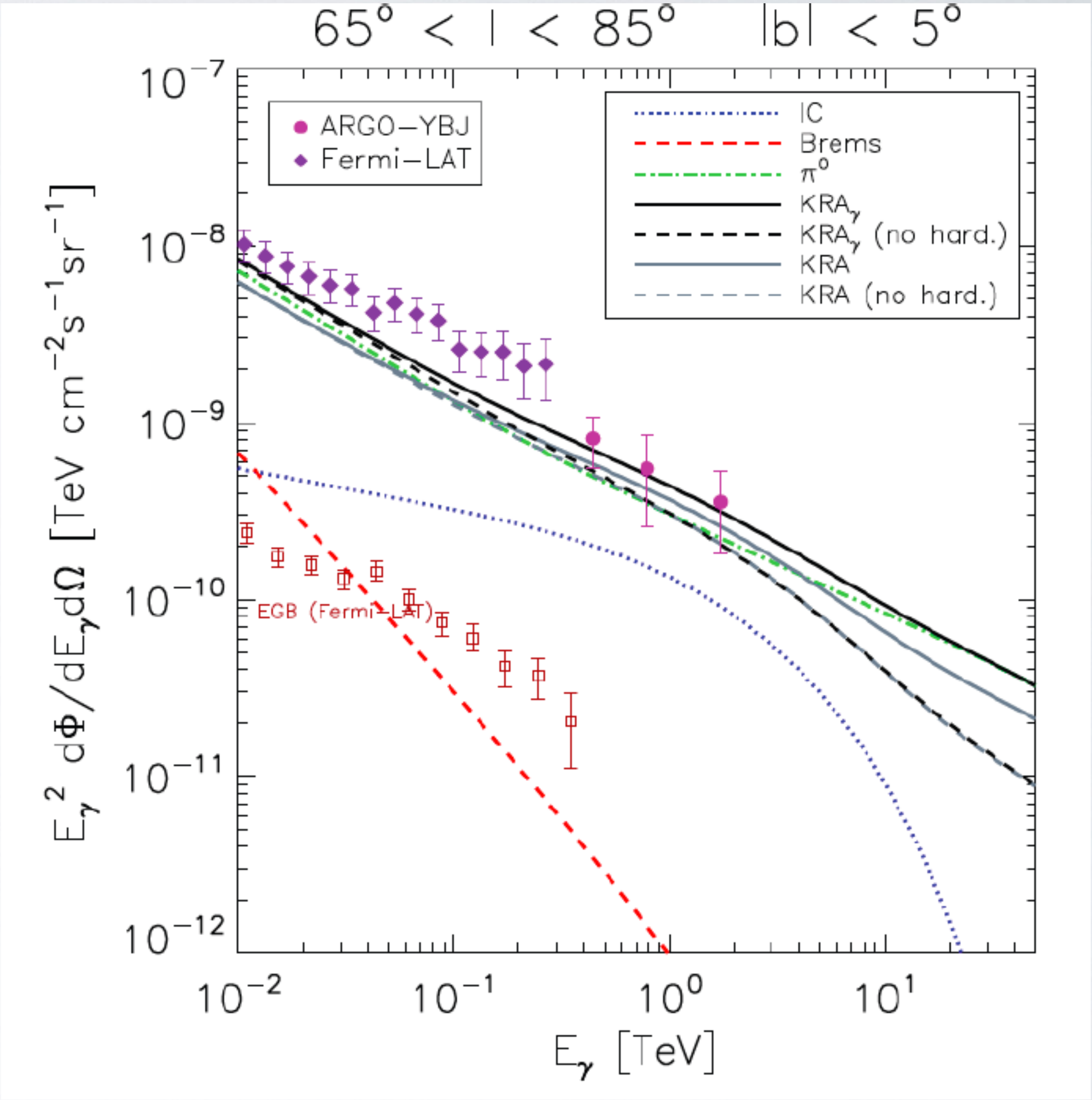
Our model against ARGO-YBJ results

ARGO-YBJ coll., ApJ 2015

the innermost region for which they released data is 65 < l < 85 deg. including Cygnus region

ARGO does not allow to discriminate among conventional and spatial dependent diffusion scenarios

The KRAγ model agrees with those data (if not preferred).



The KRAγ model against the Galactic Ridge emission

HESS (*Nature 2006*) measured a spectrum harder ($\Gamma \sim -2.3$) than expected on the basis of conventional CR models, associated with the molecular complex in the inner 200 pc of Galaxy

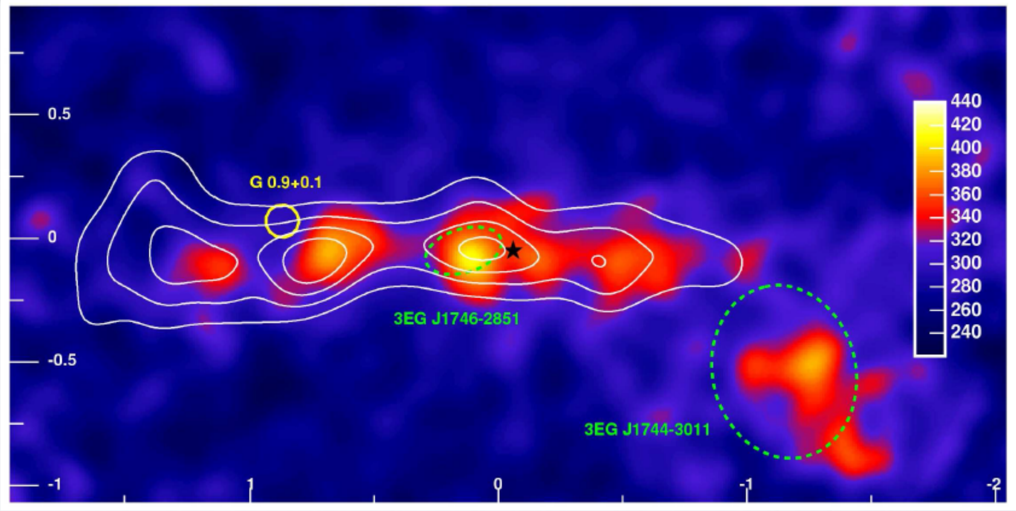
this is also the case for the updated Fermi benchmark conv. model

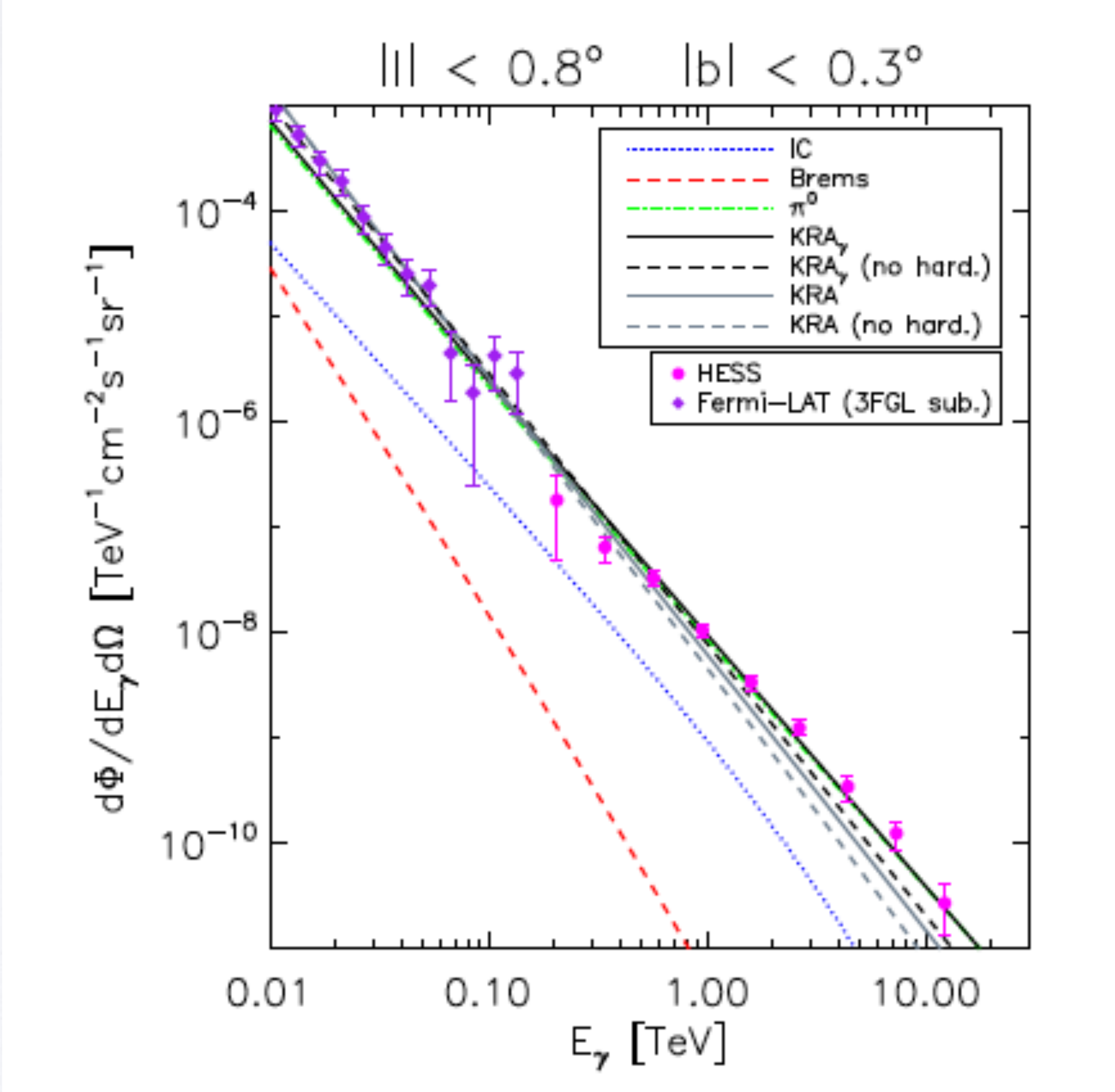
FERMI + HESS

KRAγ: $\chi2$ = 1.79 /2.27 with/w.o. hard.

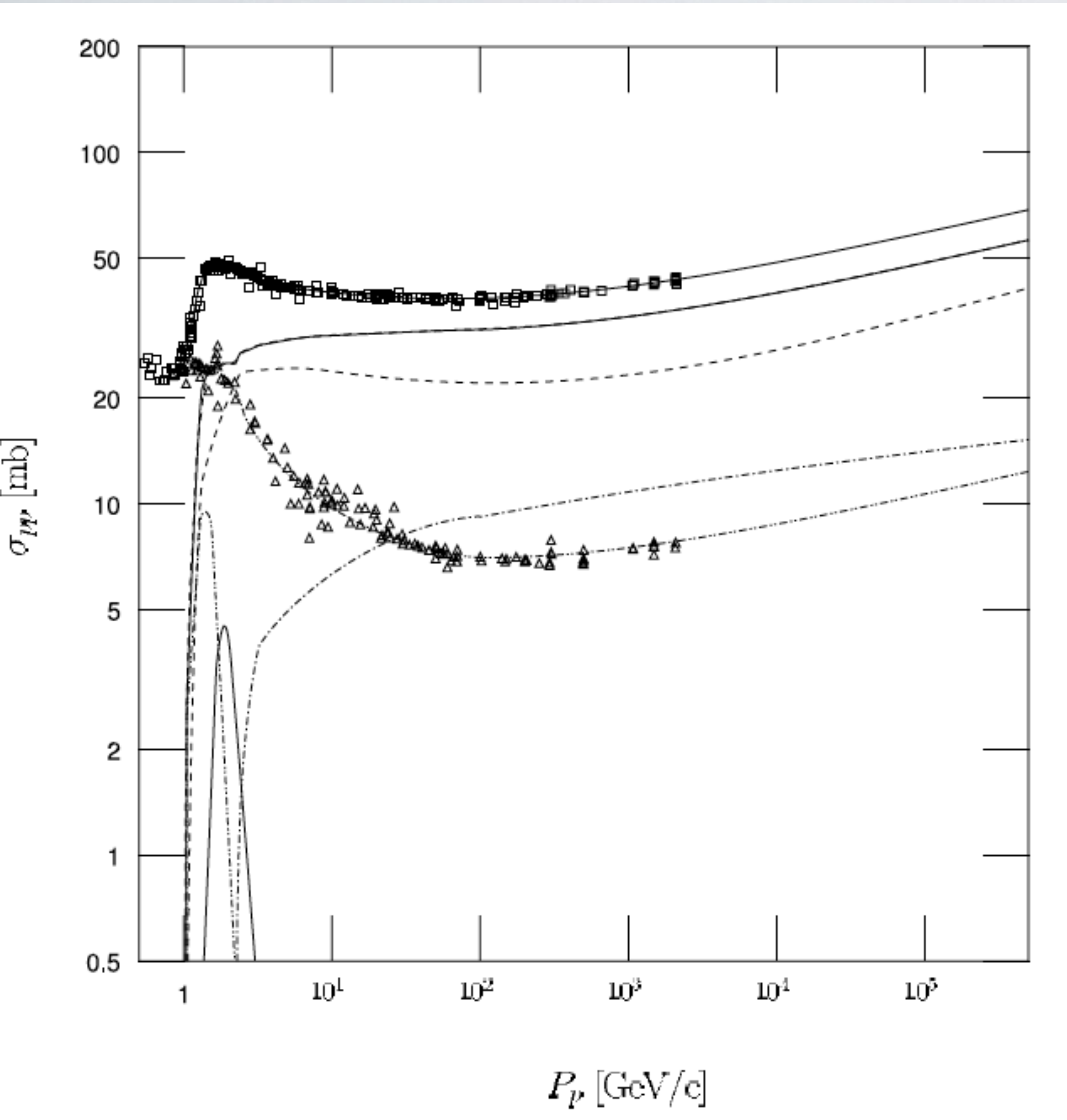
KRA: $\chi2$ = 2.92 /3.99 with/w.o. hard.

the spectrum normalization is correctly reproduced using an improved gas model in the G.C. region (*Ferriere et al. 2007*)

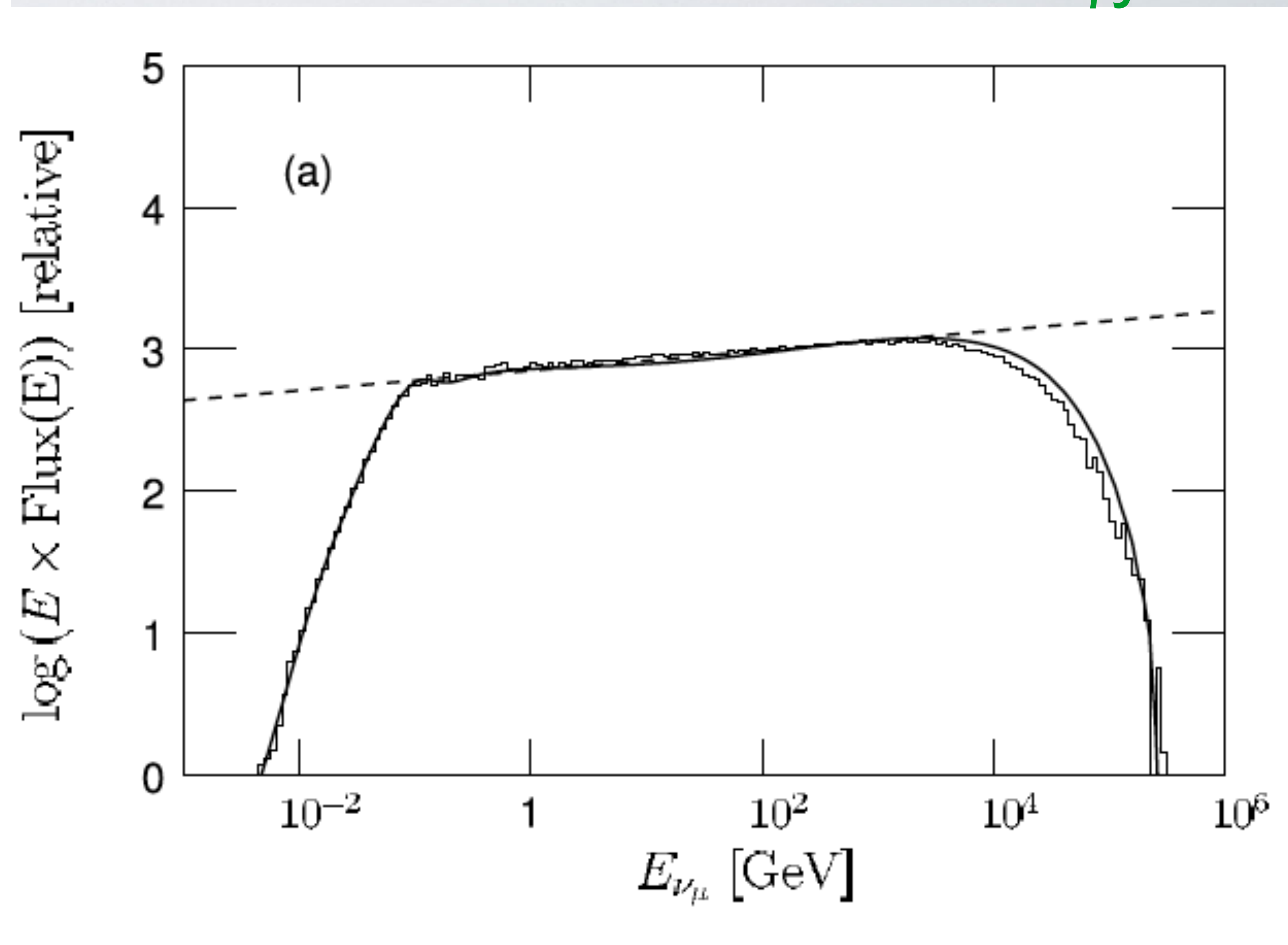




Computing the neutrino emission from CR scattering



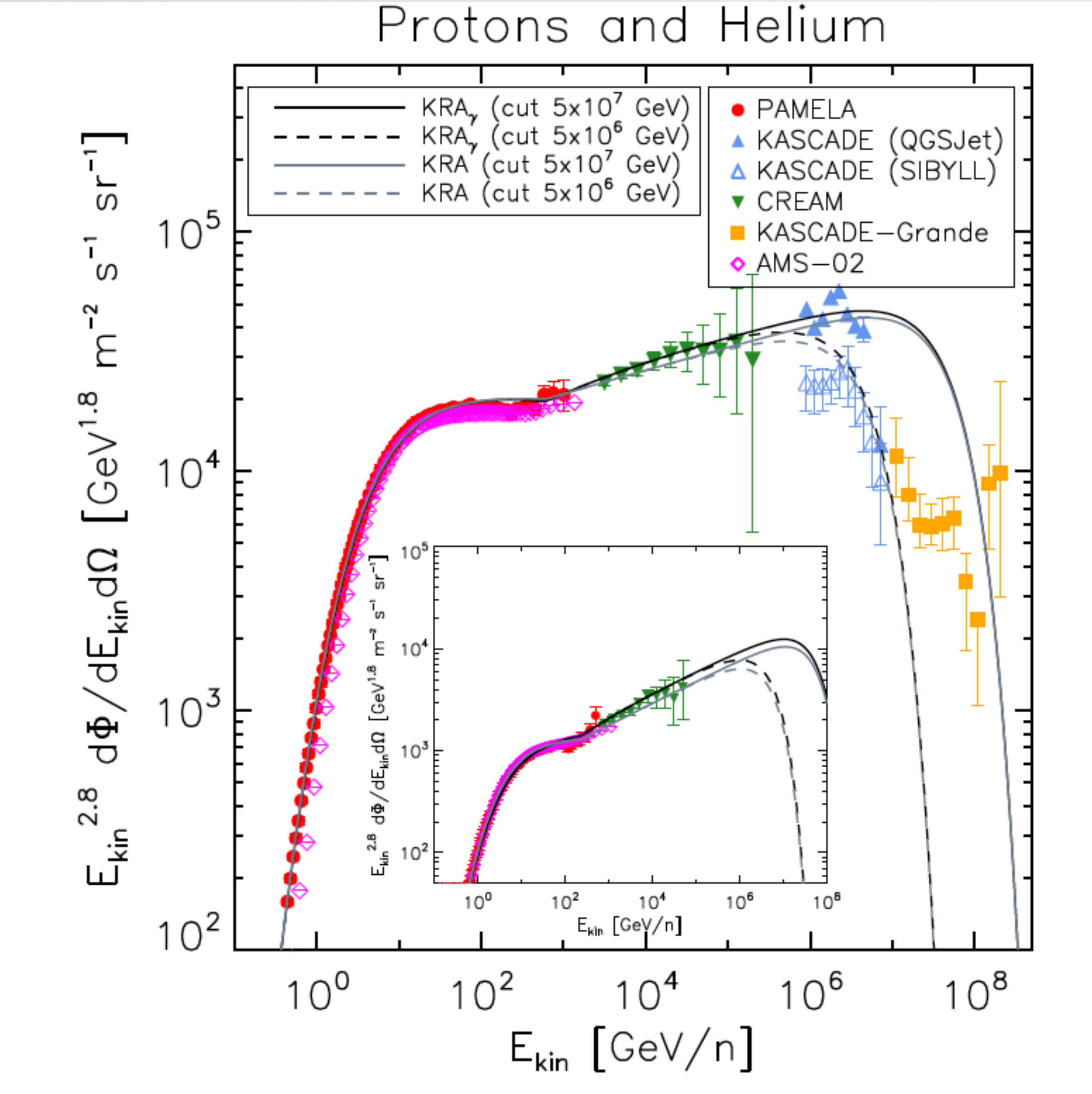
T. Kamae et al. ApJ 2006

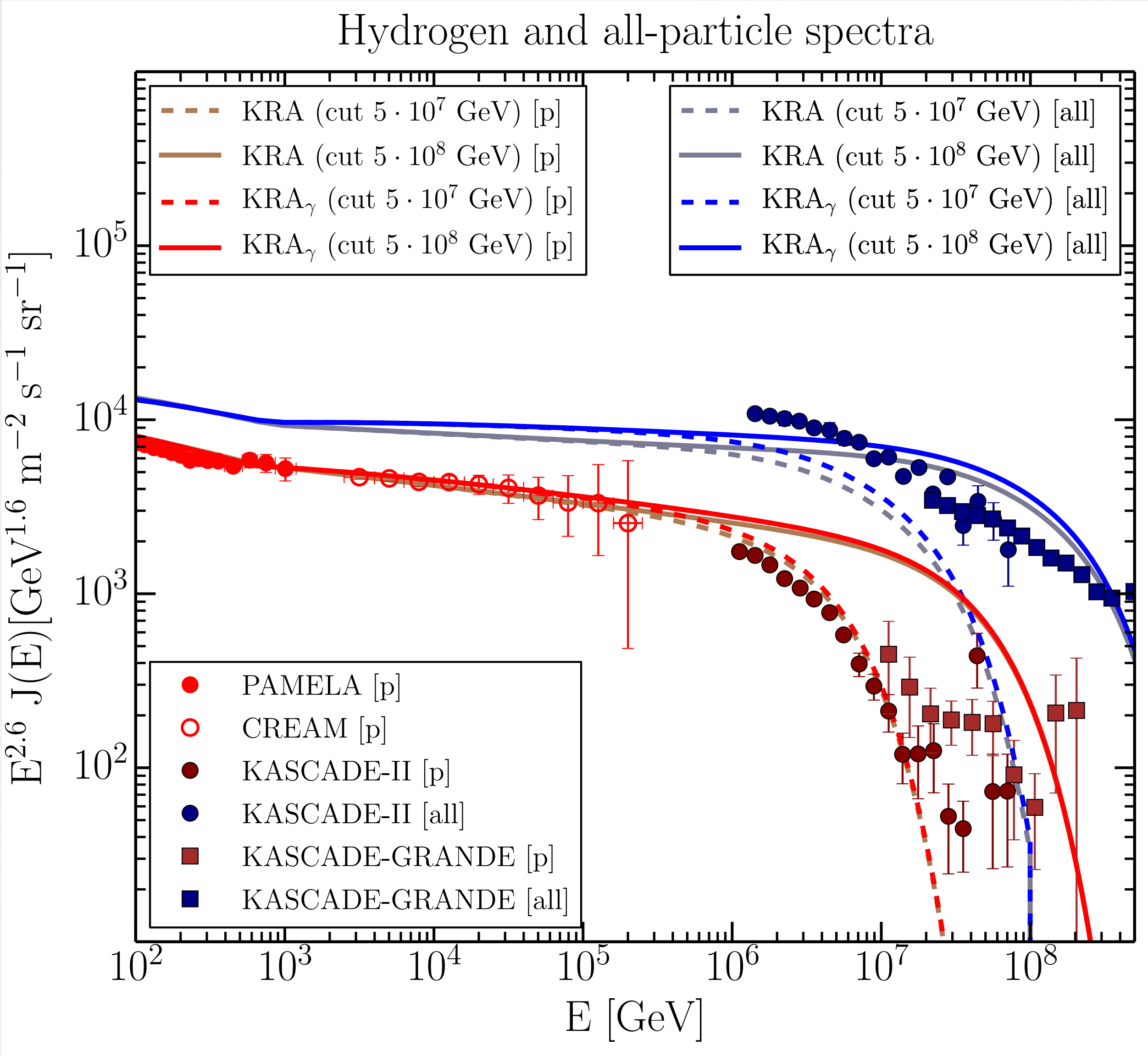


also *Kelner, Aharonian & Bugayov, 2006*

Main processes: $p + p(He) \rightarrow \pi + \text{hadrons} \rightarrow \nu_{\mu,\ e} + \ldots$

The primary spectra





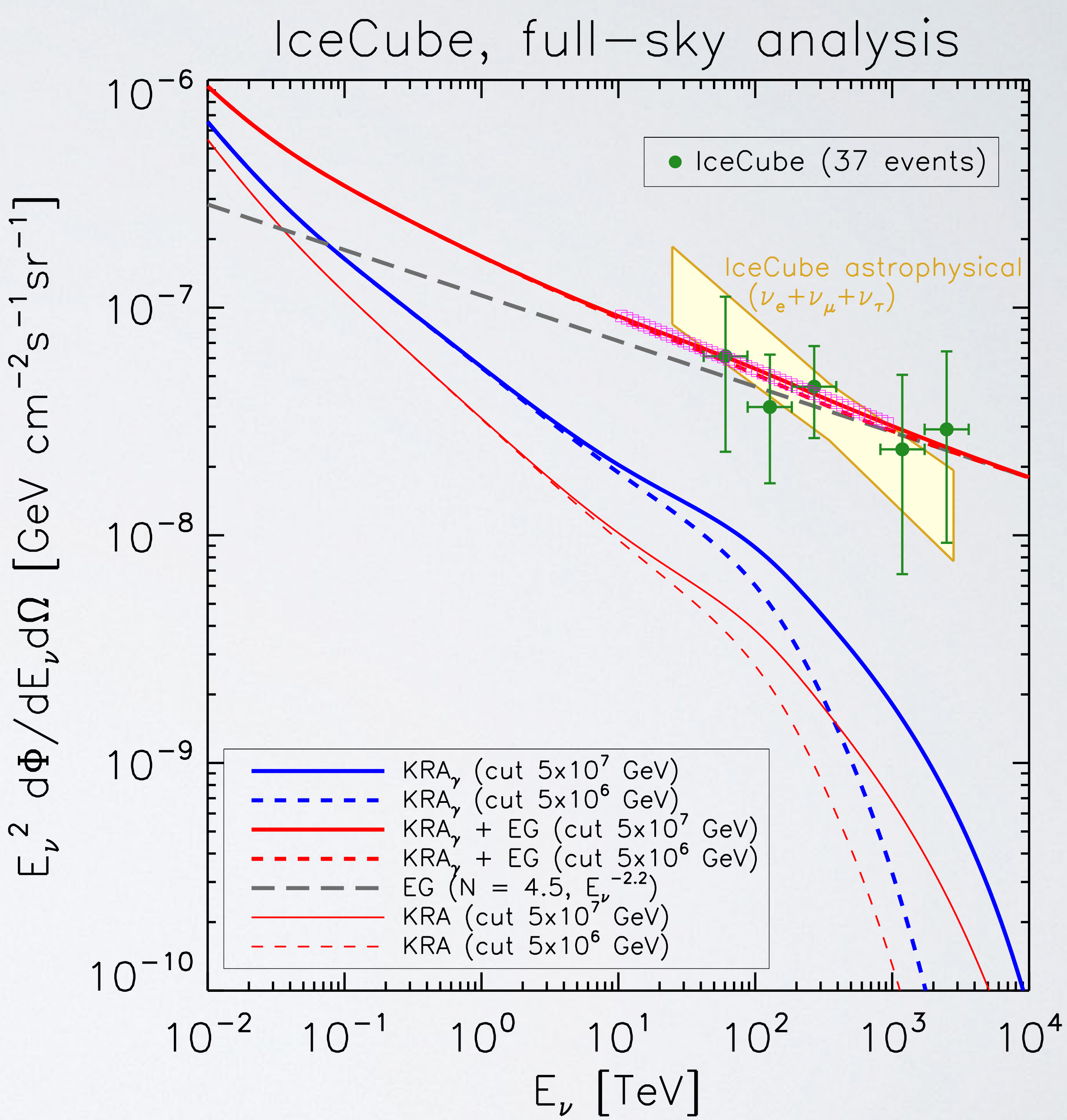
Full-sky emission computed with KRA (δ uniform) & KRA$_\gamma$ (δ variable)

Gaggero, D.G., Marinelli Urbano &Valli arXiV: 1504.00227

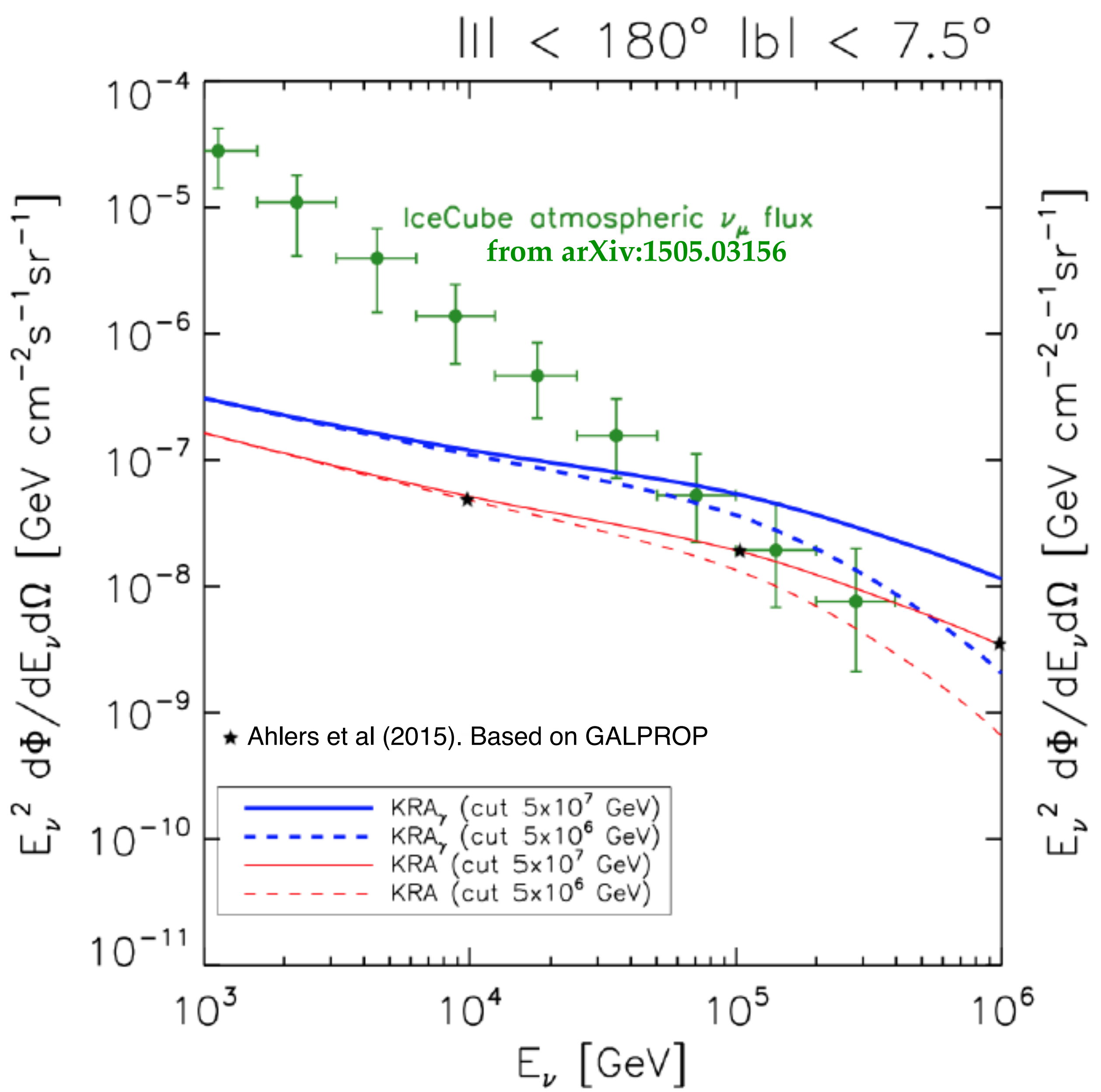
The KRAγ setup predicts a flux which is ~ double and slightly harder the conventional KRA spectrum.

This may account for ~ 15 % of the full-sky ν astrophysical flux measured by IceCube full-sky above 60 TeV (3 years HESE)

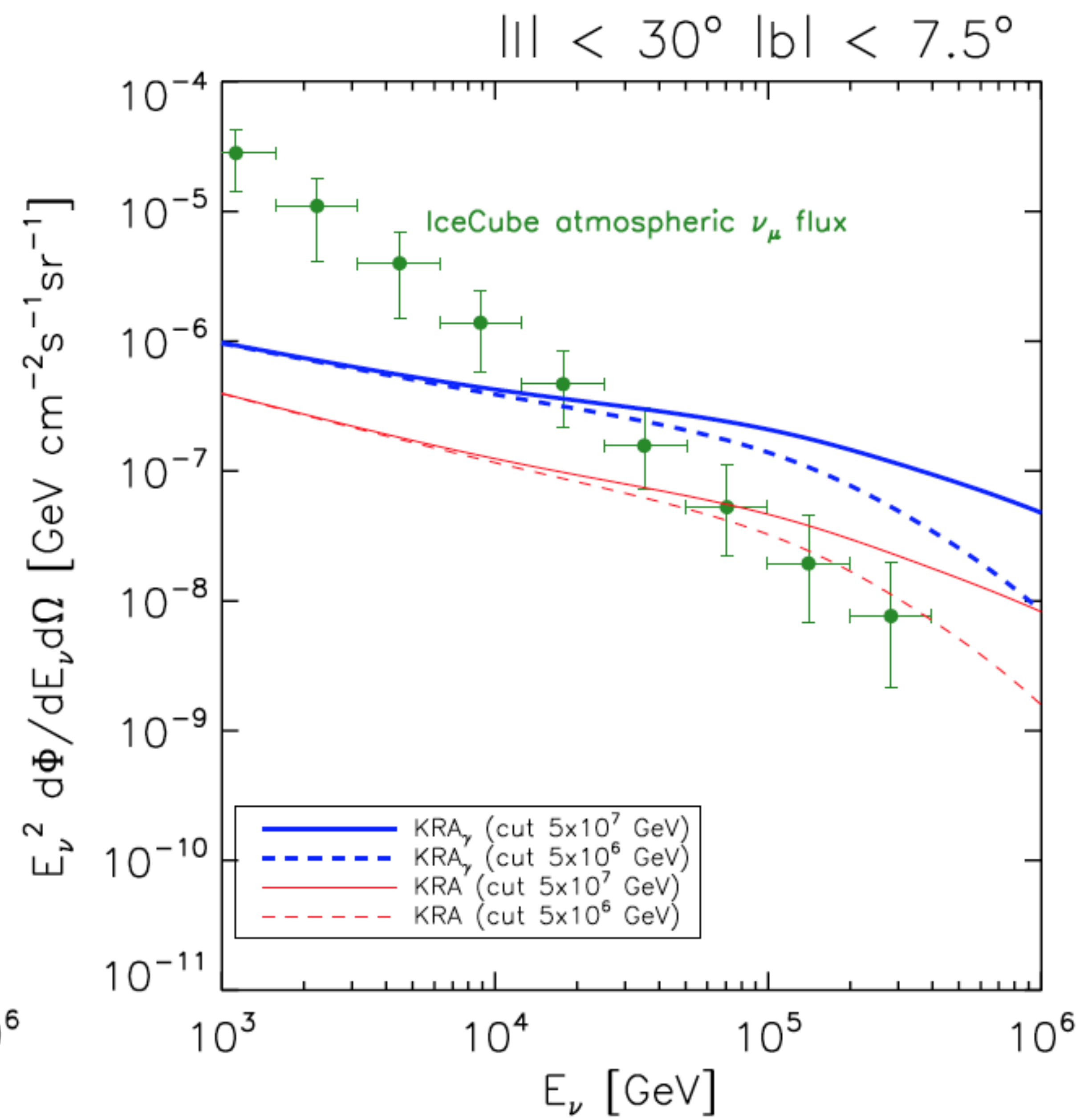
this is clearly compatible with the IC events angular distribution



Galactic Plane neutrino with KRA (δ uniform) & KRAγ (δ variable)

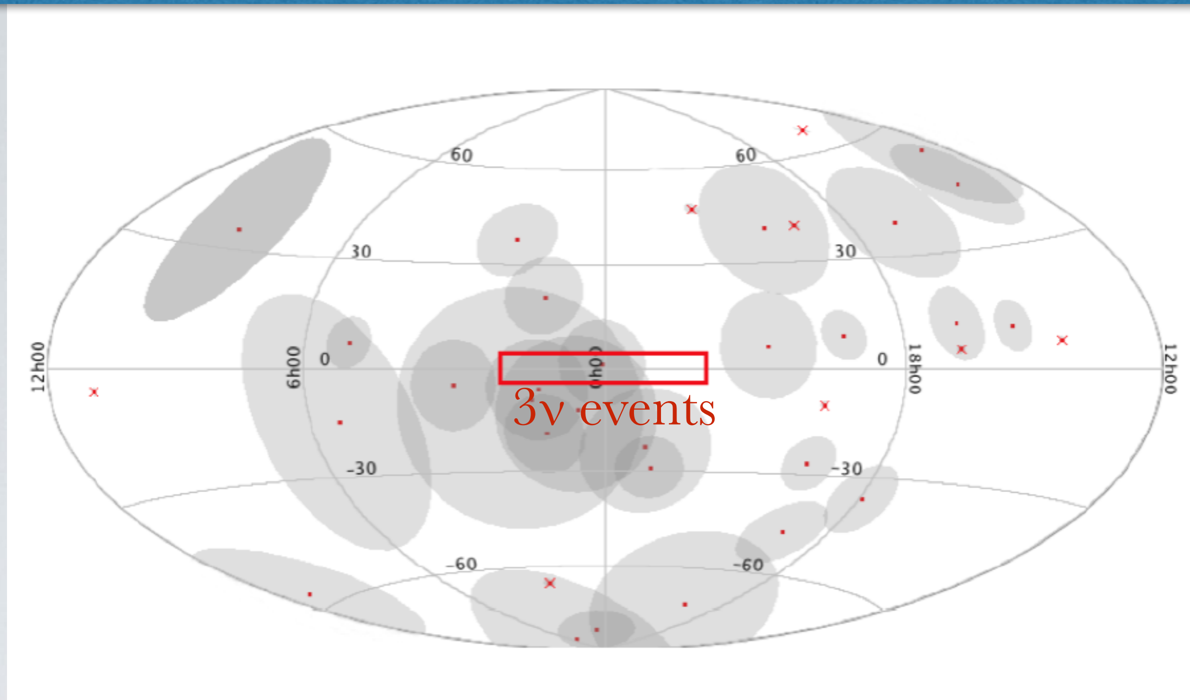


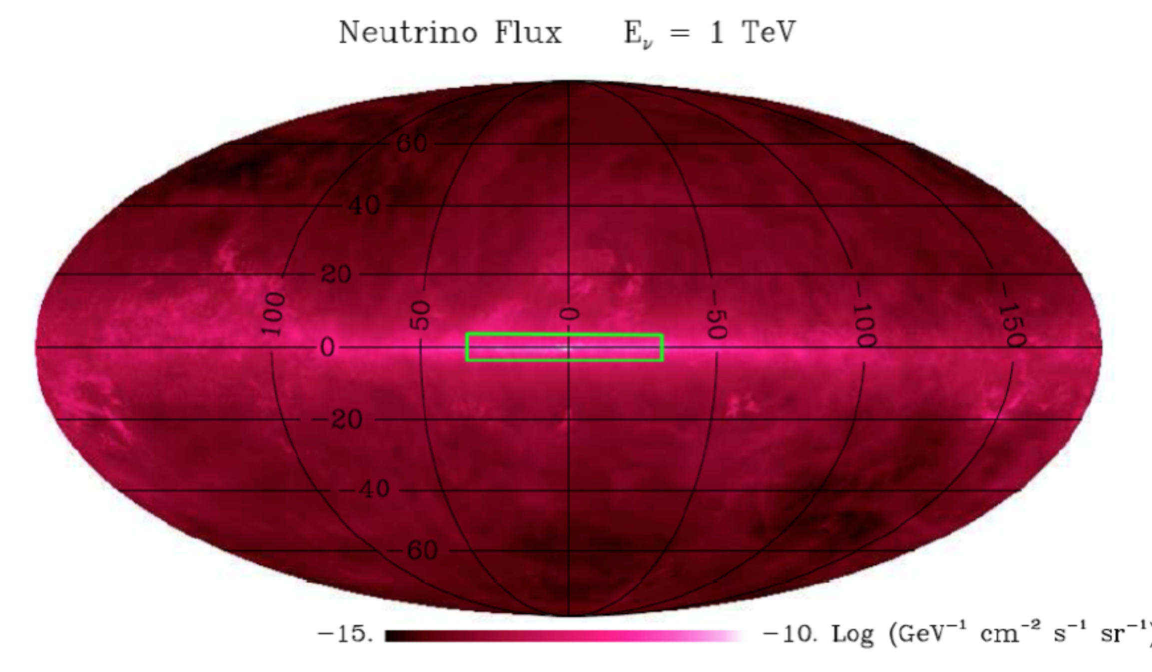
Comparison between neutrino spectrum produced with standard KRA model and the new KRAγ model from the entire galactic plane. The black stars show the equivalence between standard KRA (based on DRAGON code) and standard GALPROP obtained spectra.



The diffuse neutrino spectrum obtained considering the <u>KRAγ model for the inner galactic plane can exceed the atmospheric neutrino flux measured by IceCube above 20 TeV</u>

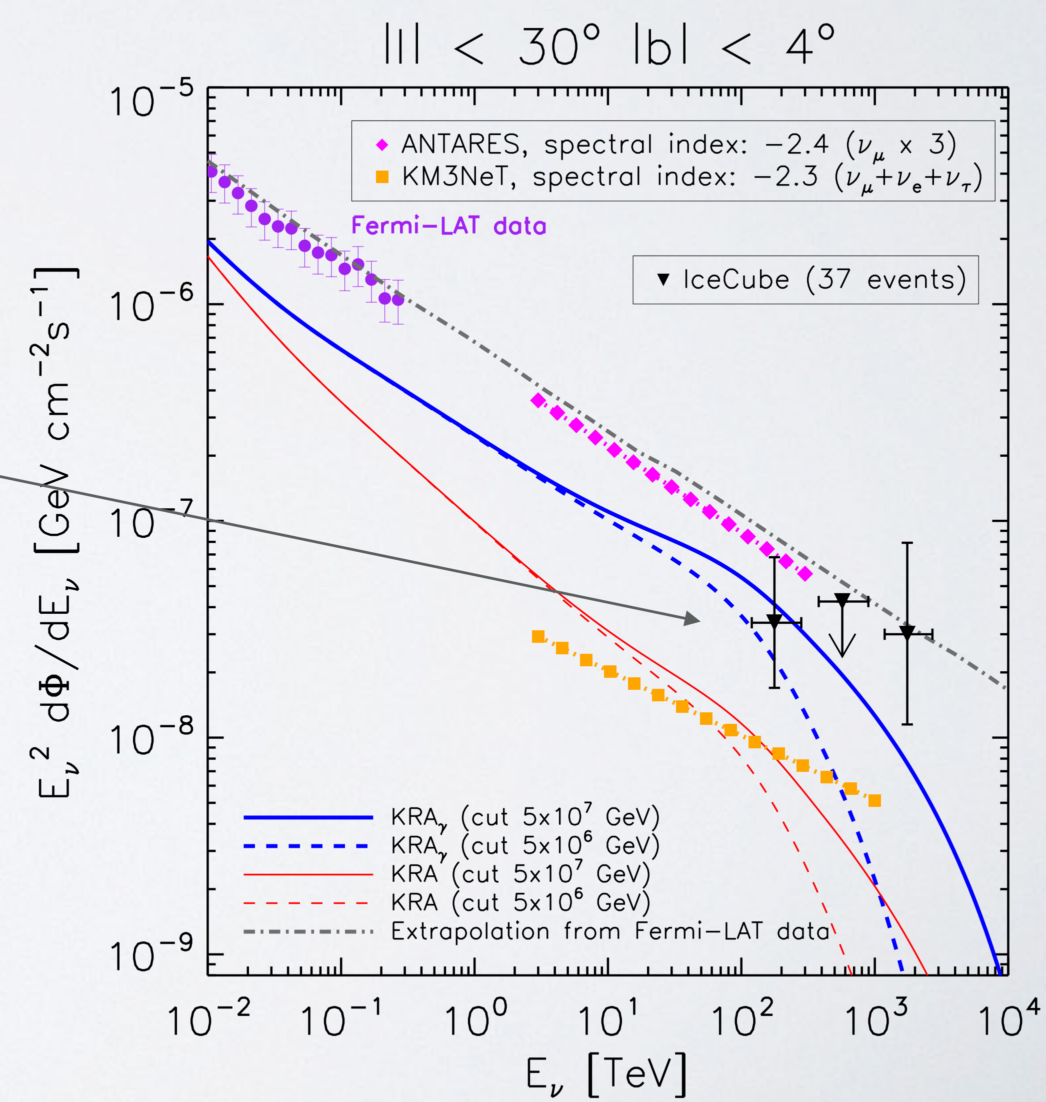
KRA and KRA$_\gamma$ neutrino spectra expected for |b|<4°, |l|<30°





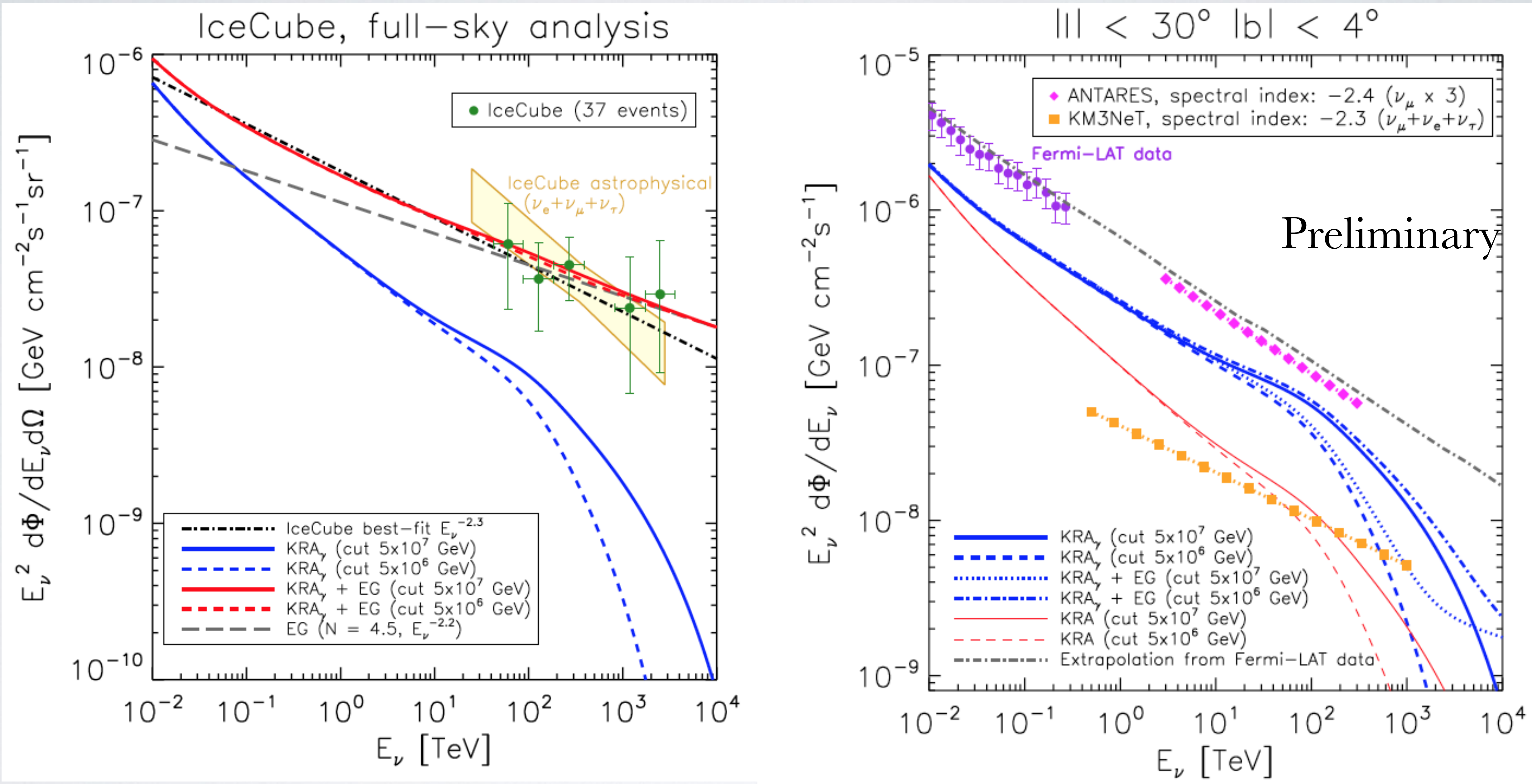
- Only 3 (shower-like) events are reconstructed in a position of the sky compatible with the |b|<4° and |l|<30° . This turns in a maximal flux in that region

- From the neutrino spectra obtained with KRA and KRA$_\gamma$ models we can estimate the galactic component of the IceCube observation in this region of the sky.



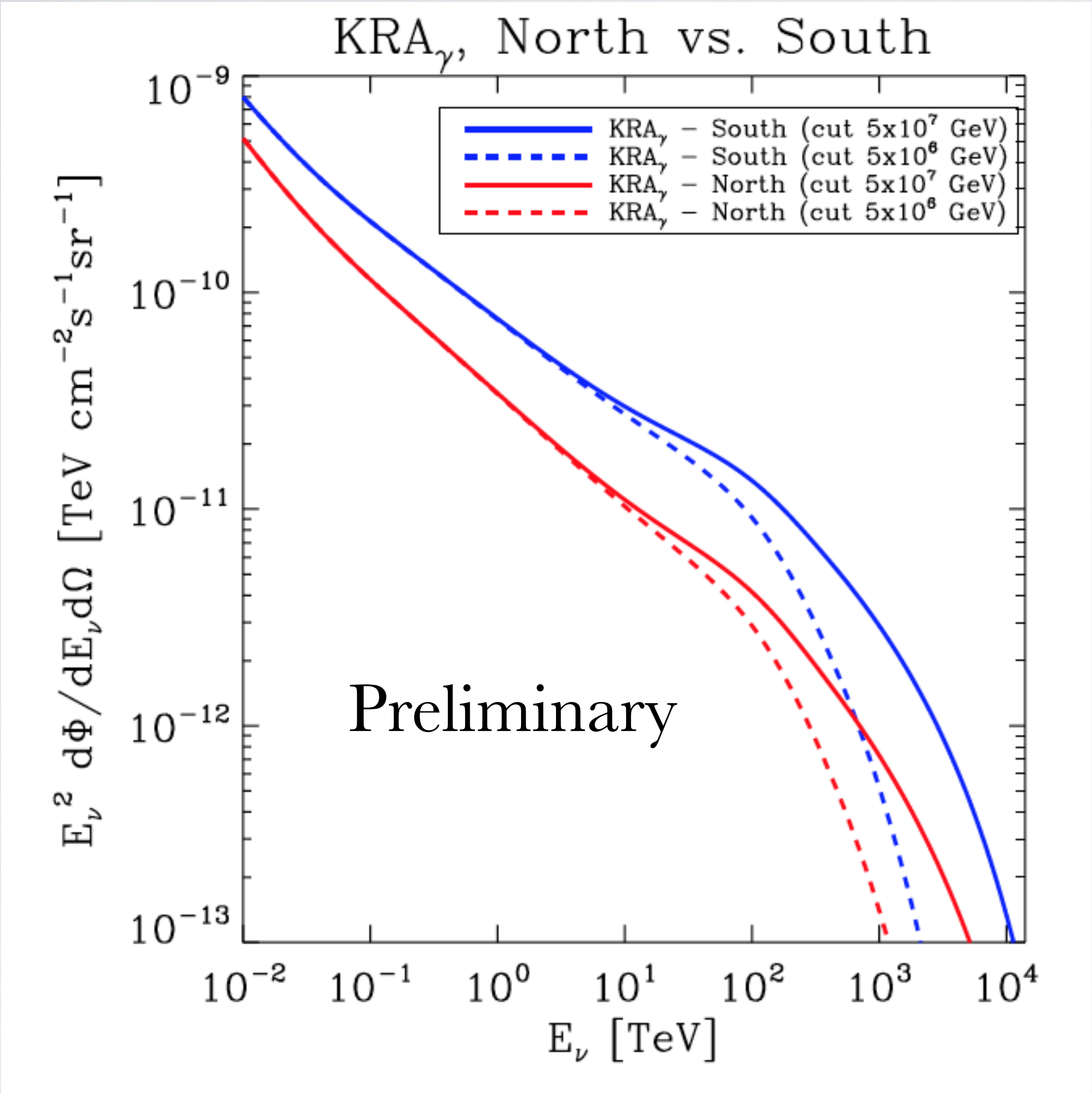
Galactic+Extragalactic expectations vs Antares upper bounds

Gaggero, Grasso, Marinelli, Urbano, Valli, arXiv:1504.00227

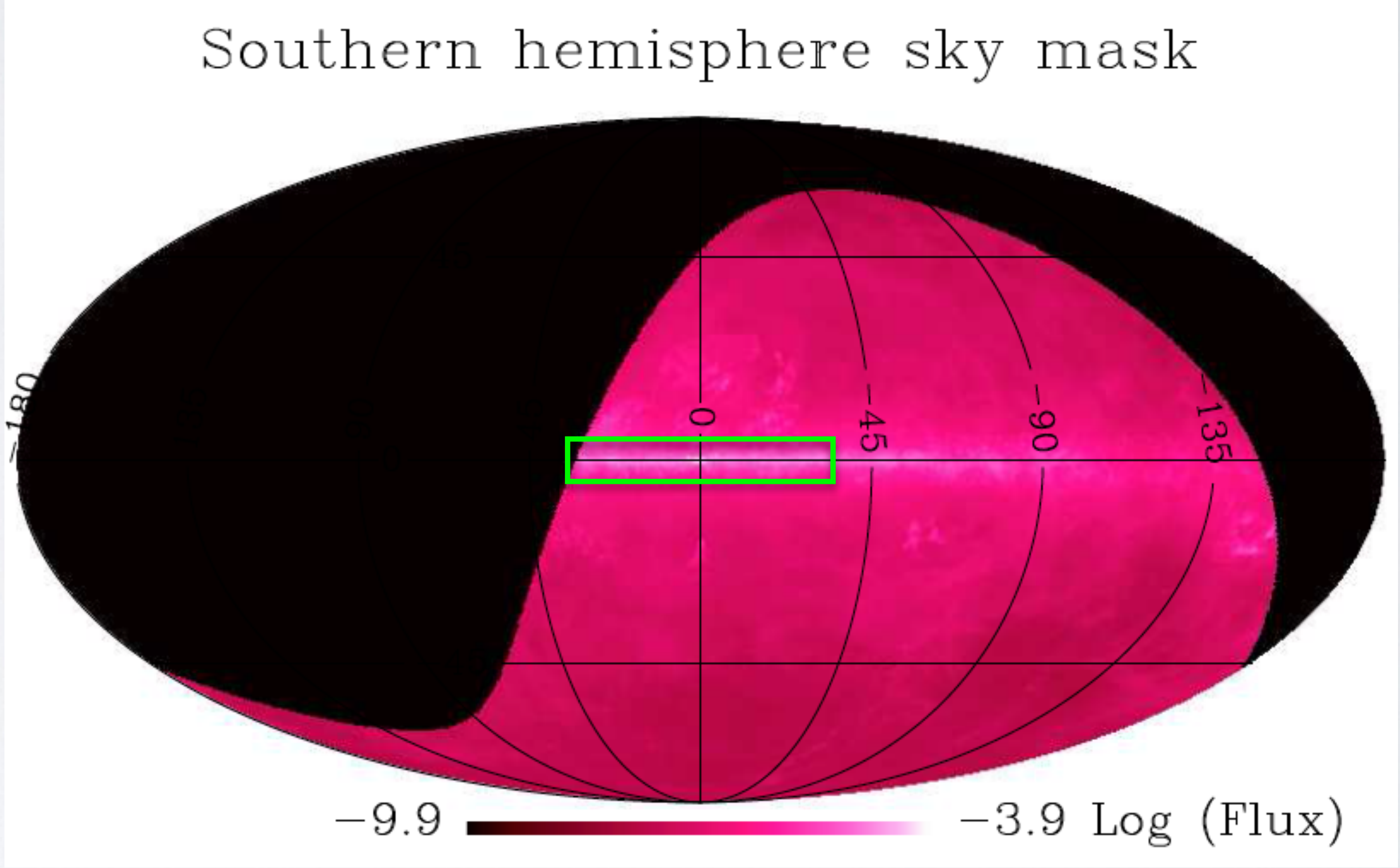


The KRAγ spectrum + extragalactic spectrum (obtained from the muon neutrino analysis of the Northern hemisphere) give a physical meaning to the IceCube full sky measured spectrum and is still consistent, in the ridge region, with the **Antares measured upper limit** (*Fusco et al. [ANTARES coll.] ICRC 2015*).

The expected KRAγ neutrinos from north/south hemisphere



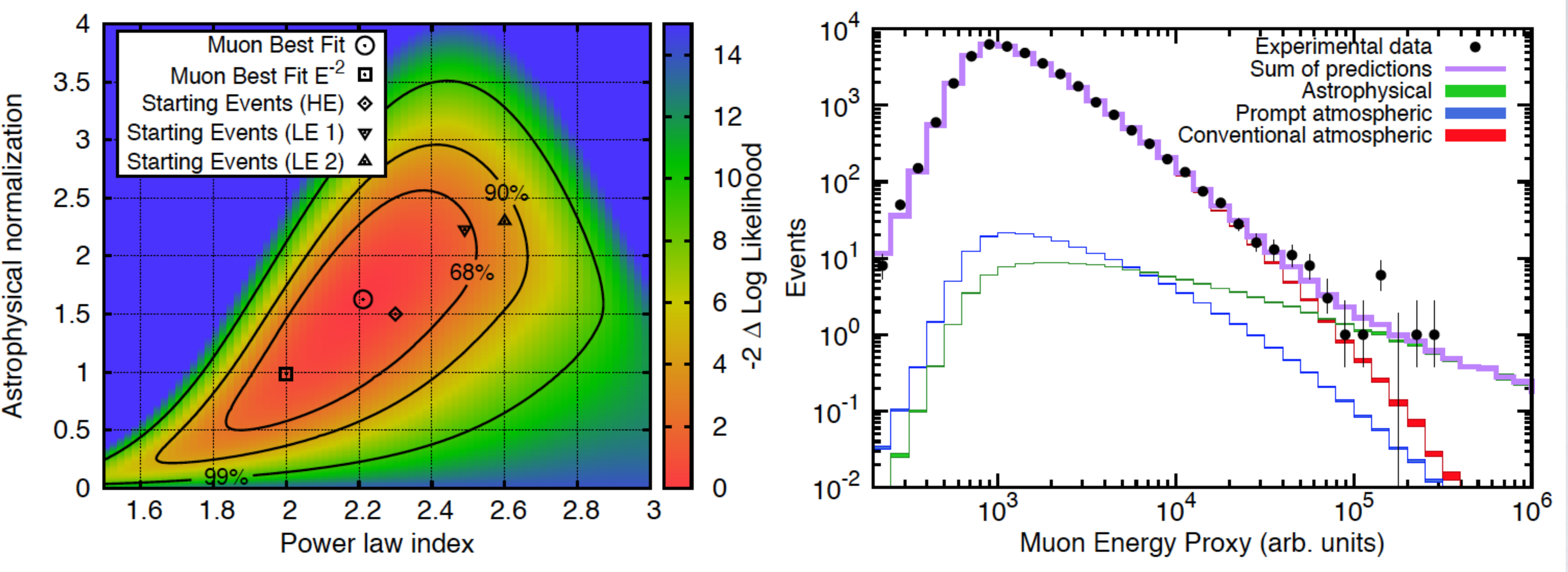
The Southern hemisphere expected neutrinos, obtained with KRAγ scenario, are more than double the expected from the Northern one.



The inner galactic plane neutrino diffuse emission mostly comes from the Southern hemisphere.

Estimating the extragalactic contribution from the North hemisphere

IceCube coll., PRL, vol.115, n.8, 2015

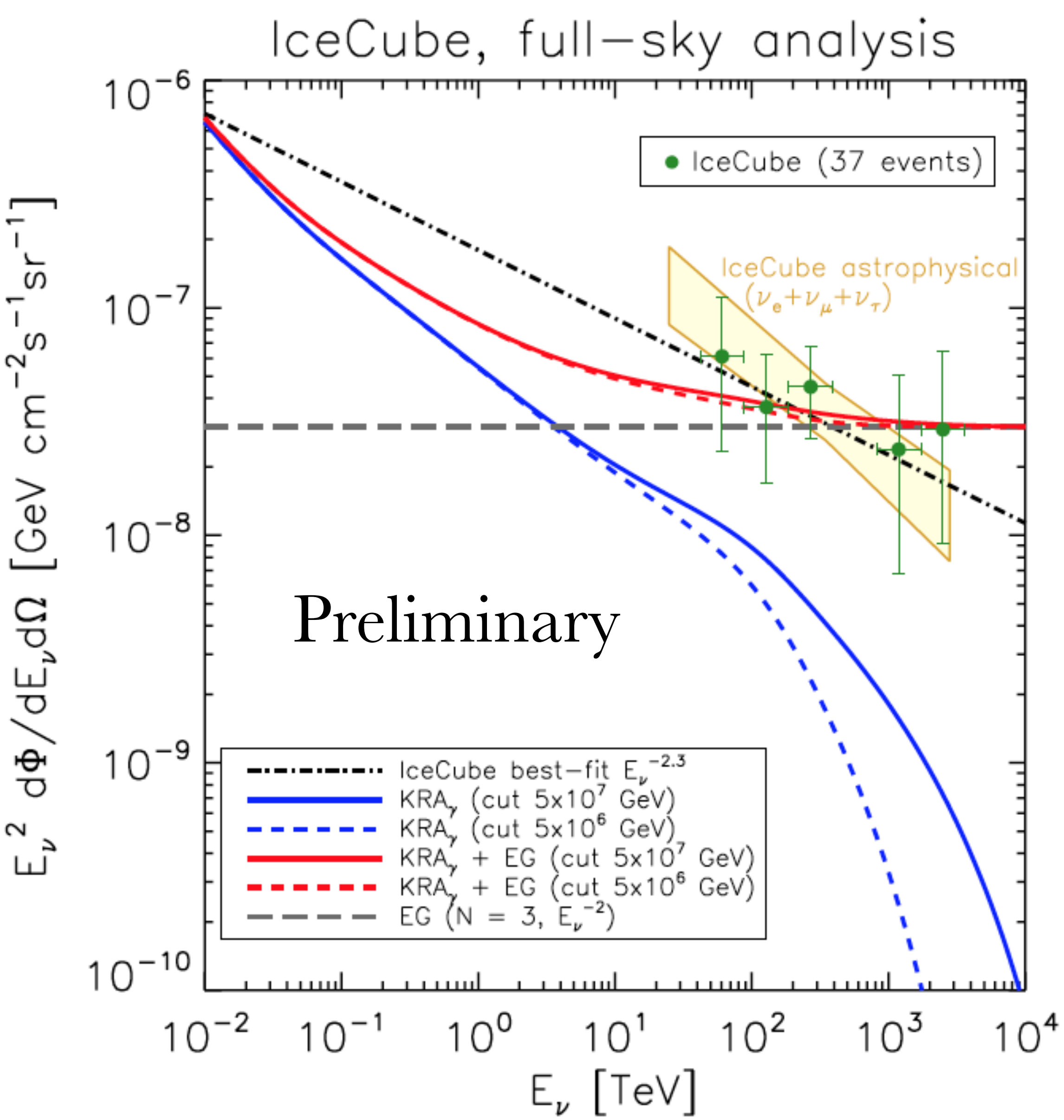


- IceCube collaboration recently published a evidence of astrophysical muon neutrinos from the Northern hemisphere. The neutrinos collected during 659.5 days of live time between May 2010 and May 2012 are inconsistent with the background at the level of 3.7 σ.

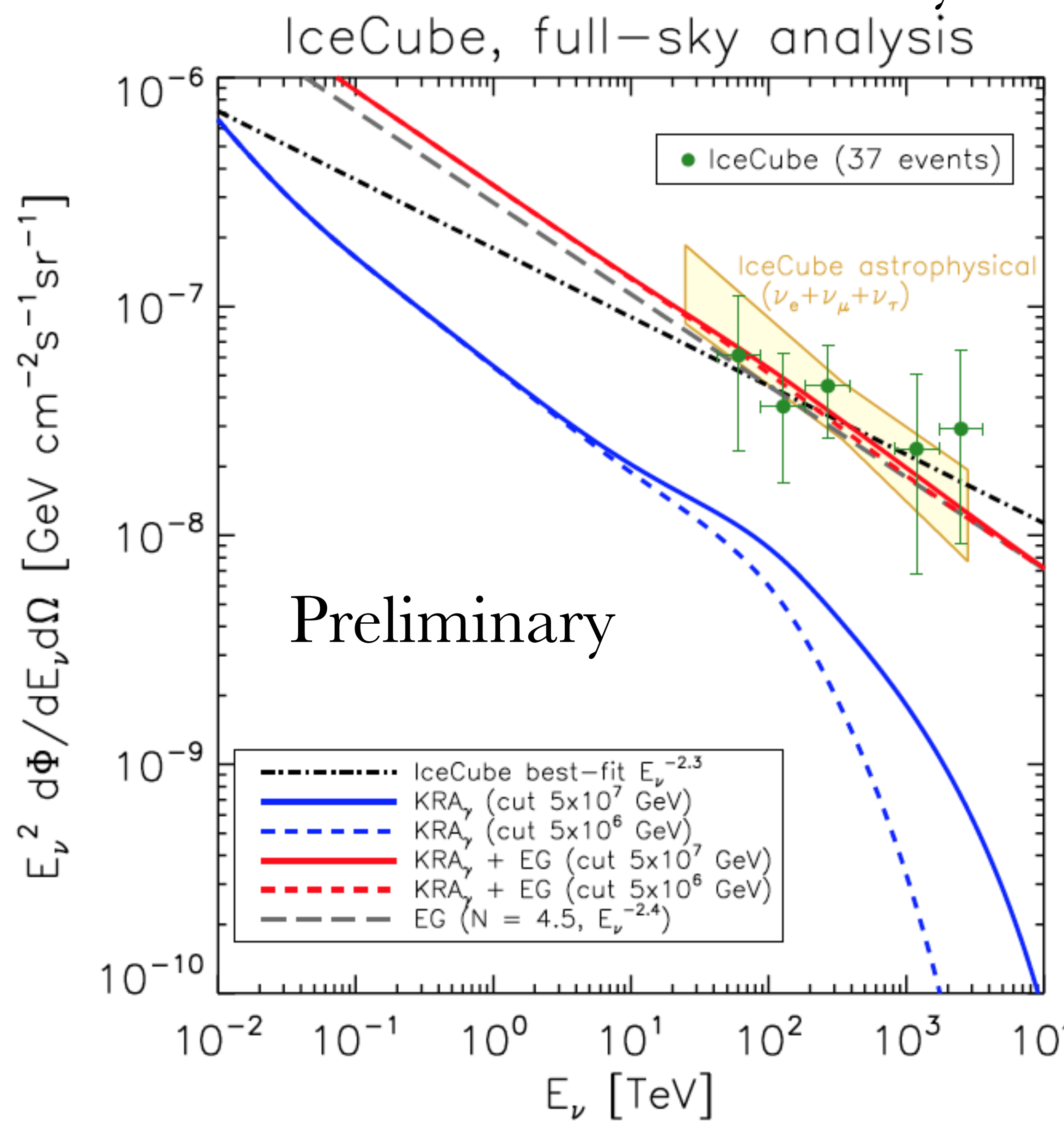
- Assuming a modest diffuse galactic contribution from this hemisphere we can consider the observed muon neutrinos as a good bound for the extragalactic neutrino signal. In this case the best-fit analysis gives a Γ ~ 2.2 .

Looking at Galactic + extreme Extragalactic scenarios

Extragalactic $\Gamma = 2$



Extragalactic $\Gamma = 2.4$
(may be problematic with
the EGRB measured by Fermi)



These extragalactic scenarios are still compatible with Antares upper limits when adding the KRA_γ neutrinos, however are less coupled with the full sky IceCube spectrum.

CONCLUSIONS

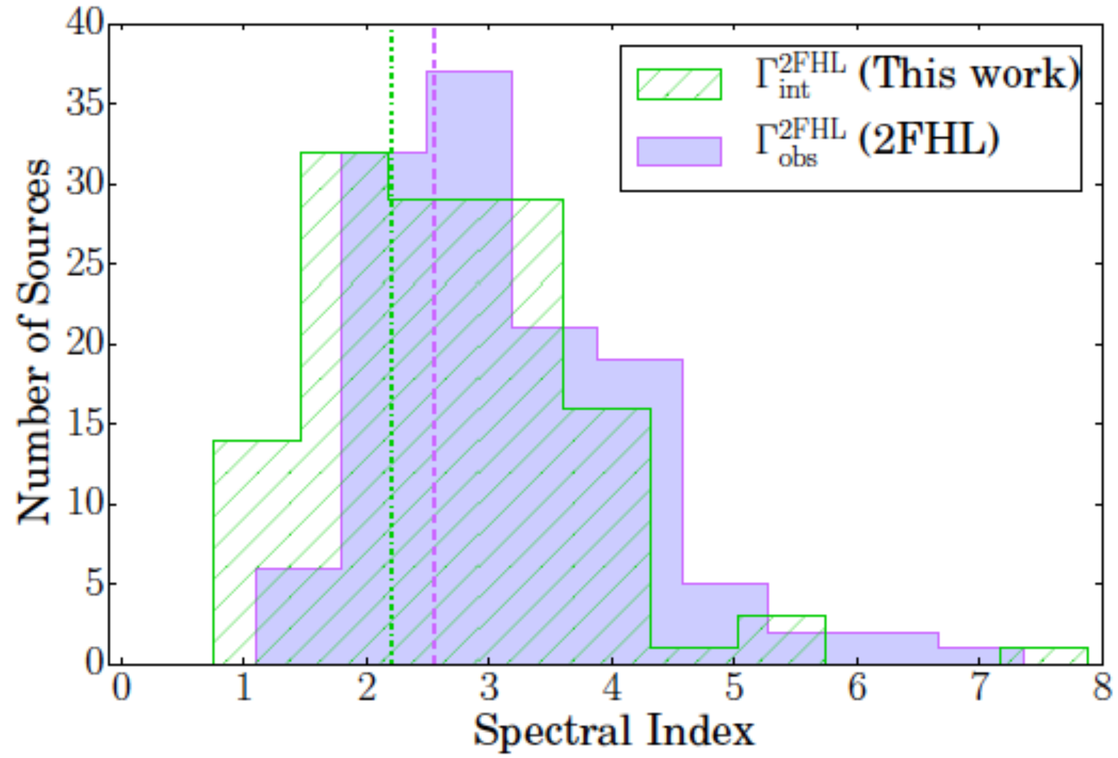
- The γ-ray Galactic diffuse emission measured by Fermi can be interpreted in terms of a radially dependent CR transport model. The same model, when accounting for the CR hardening at 250 GeV/n, allows to reproduce Milagro excess at 15 TeV
- expect to conventional models this scenario predicts a significantly larger Galactic neutrino flux along the Galactic center/plane testable by IceCube, ANTARES (marginally) and Km3NeT
- Full-sky the Galactic emission which may partially help interpreting the possible evidences of a Galactic component in the IceCube signal.

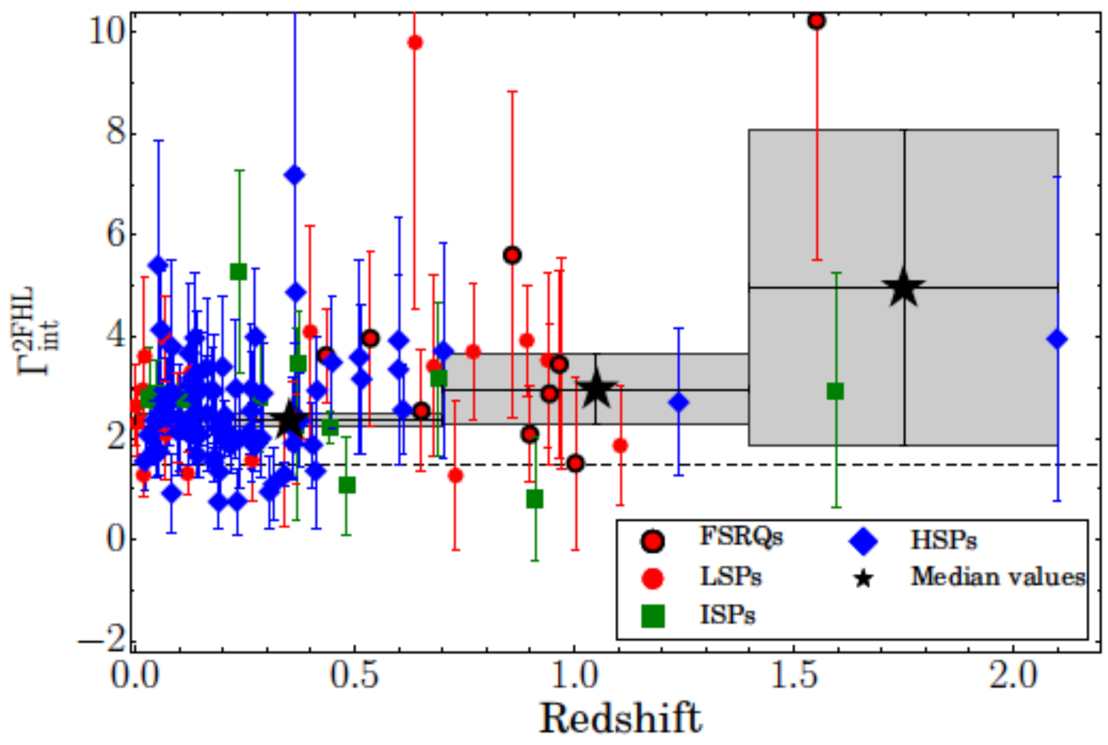
DRAGON

- solve the diffusion equation on a 3D (r,z,E) grid (now also 4D!)
- realistic distributions for sources and ISM
- different models for fragmentation cross sections
- position dependent, anisotropic diffusion
- independent injection spectra for each nuclear species
- speed and memory high-performances (full C++)
- public: http://www.dragonproject.org

A class of extragalactic sources compatible with Γ ~ 2.2

Dominguéz & Ajello, ArXiv:1510.07913





- A analysis of 128 extragalactic sources (mostly Blazars) from the 2FHL (E>50 GeV) catalog set the average intrinsic (unattenuated from the EBL) spectral index at Γ ~ 2.2 versus the measured average Γ ~ 2.5
- If the gamma-ray are produced through pion decay we can expect a corresponding neutrino spectrum described by the obtained intrinsic Γ ~ 2.2 .

Ahlers 2014

5th Fermi symposium

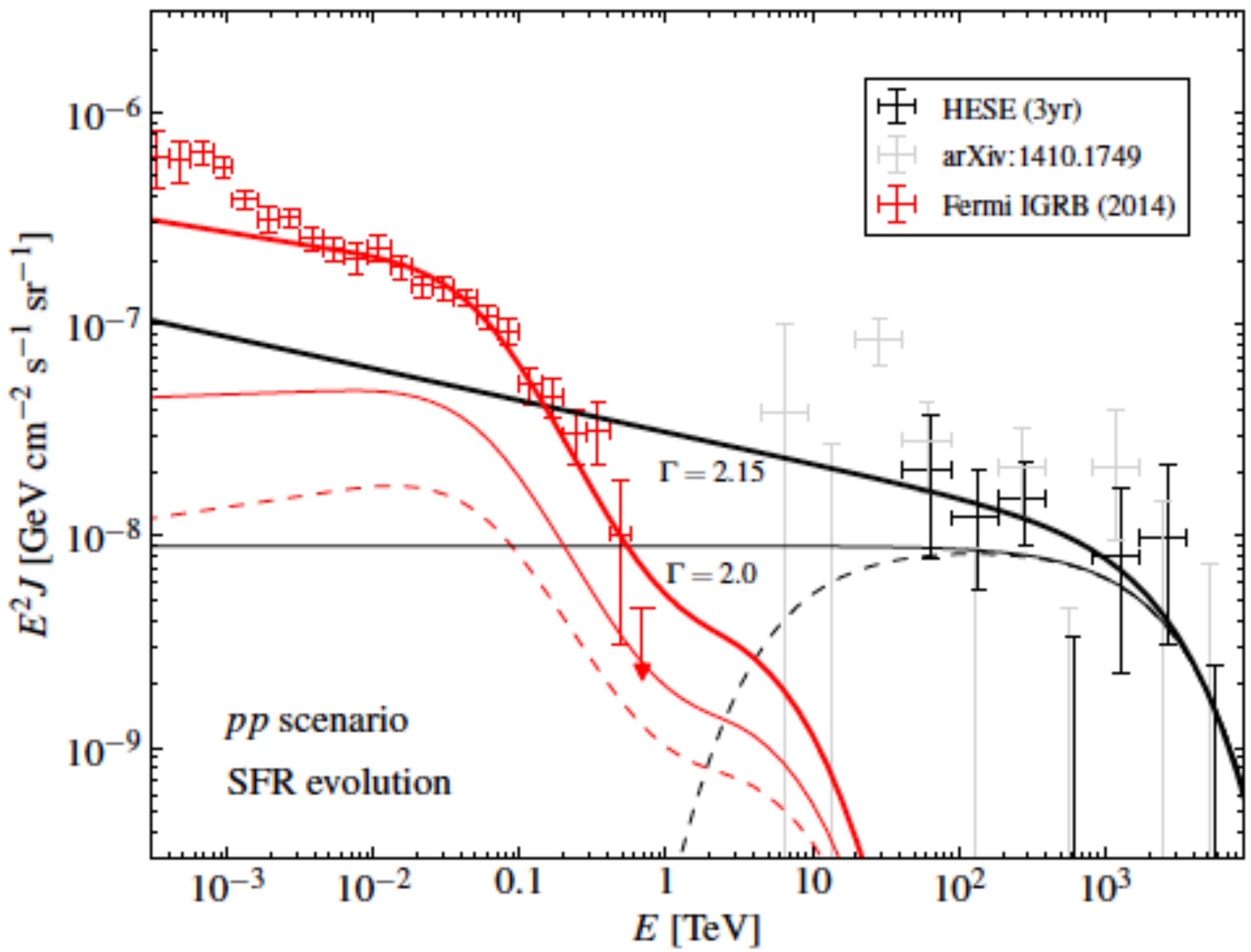


Figure 3: Isotropic γ-ray background (IGRB) inferred by *Fermi* [70] compared to the diffuse per-flavor neutrino flux observed by IceCube[1, 4] (updated plot of Ref. [36]). The black lines show possible neutrino models consistent with the IceCube data. The red lines are the corresponding γ-rays of *pp* scenarios reprocessed in the cosmic radiation background. The thick and thin solid lines show a power-law emission with $\Gamma = 2.15$ and $\Gamma = 2$, respectively, with an exponential cutoff around PeV. The dashed lines show an emission that is peaked in the 10TeV-PeV and only contributes in the γ-ray emission via cascades photons.